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Food security: Sustainability and accessibility

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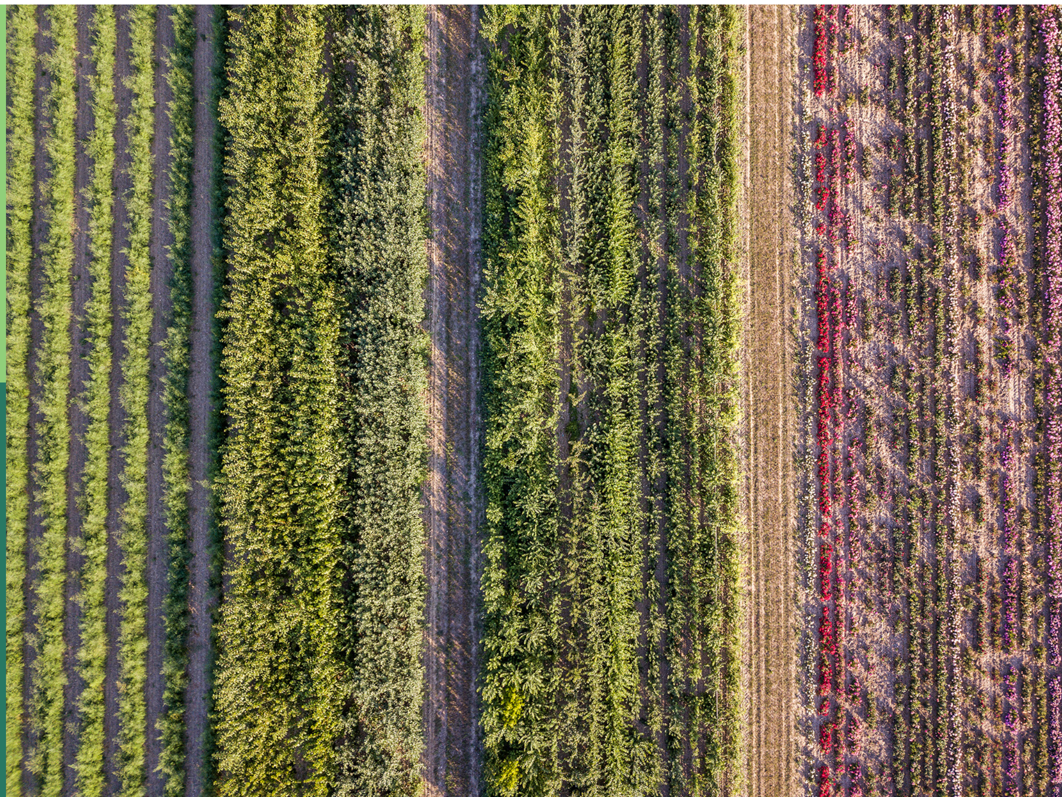

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Food security: Sustainability and accessibility

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Editorial: Food security: sustainability and accessibility

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Editorial on the Research Topic
Food security: sustainability and accessibility

The enhancement of agricultural productivity in response to food crises poses severe environmental degradation, which has been undermined to feed the world's growing population. The State of Food Security and Nutrition in the World Report, FAO (2018) outlined the failures of human responses toward "Zero Hunger" and nutritional fulfillment. The Global Report on Food Crises (2023) estimates that over a quarter of a billion people were acutely food-insecure and required urgent food assistance in 58 food-crisis countries/territories in 2022. Similarly, the Global Hunger Index report (2022) highlighted the severe hunger in 44 countries, including 828 million people in the world; South Asia and parts of Africa south of the Sahara are highly susceptible to food crises in future (Resnick et al., 2022). The striking global food crisis is the integration of remnant disruption of socio-economic settings, inequalities, inaccessibility and ecological imbalance. The consequences of anthropogenic climate change have drawn attention and are a crucial driver of global food crises and malnutrition. Hence, enduring sustainability in food productivity with opportunities for accessibility plays a vital role in achieving long-term food security.

Ajibade et al. have highlighted the importance of Sustainable intensification of agriculture to meet the demand of growing populations' nutritional needs while limiting environmental degradation. The research analyzed the scientific output on sustainable agriculture for the last decade in the globe using bibliometric analysis, which revealed that (1,610) studies were conducted on sustainable agriculture by (6,346) authors belonging to (1,981) organizations over (115) countries. The number of publications and citations on sustainable agriculture increased in 2020, with 293 publications and 10,275 citations.

The effectiveness of artificial insemination concerning the food and nutritional security of smallholder pig production systems of the Indian Himalayas was discussed by Singh et al.. The result shows an 87.33% increase in net returns per farrowing due to artificial insemination compared to natural breeding.

Coffee is the economy of Ethiopia and is well-known for its quality in the global market. Despite this, the study on food security in the coffee-growing communities in Yayu of Southwestern Ethiopia by Jemal et al. found that 83% of households were hunger-free in the shortage season but that dietary diversity was inadequate. The surplus season brought over 50% of children under five and women without heme iron-containing foods, while the shortage season brought 88%.

Tian and Liu explored China's agricultural investment along the Belt and Road, wherein the Zero-inflated Poisson Model was applied. The authors referred to the advancement in regional cooperation in farmland investment, livelihood security in less developed regions, grain security in developing countries and conservation of water and land resources while valuing the distribution and sales of agricultural products in the Belt and Road countries.

Moore et al. highlighted the crucial role of women's decision-making as a point of entry to improving nutritional outcomes of children through changes in empowerment, as it can determine the resource allocation within the household.

Food insecurity and income inequality are critical issues in developing countries. A study on the impact of urban safety net on income, food expenditure and intake capacity of poor households in Addis Ababa city, Ethiopia, by Tareke outlined that the cash transfer program has potentially uplifted the economic condition of the marginalized communities and able to enhance the diet intake. Research suggested effective policy interventions to improve the regularity and amount of cash transfers and supplies of emergency aids by implementing skill development programs.

Conservation agriculture exhibits a more incredible response to the ill impact of weed and pest infestation. Raj et al. underlined how zero tillage-based triple cropping with residue management and herbicide help control weed and pest infestation. This conservation agriculture practice could be a possible alternative to puddled transplanted rice in India's North-wester Indo-Gangetic Plains and similar agroecological zones of the tropics and sub-tropics.

Ahmad Rizal and Nordin explored the critical determining factors for the adaptability of innovation by the farmers to combat the food crisis in Post COVID-19 era, considering the studies over the last 15 years using PRISMA-P based on the SCOPUS and Web of Science database. The authors underlined that technological adaptability in the farmland could increase productivity and help ensure food availability and nutrition.

Ukraine's war has resulted in mass displacement of the human population and disrupted the socio-economical settings of the communities, leading to a severe global food crisis. Hereafter, Russia and Ukraine's high dependency on food grains drives the Middle East countries to a critical food crisis. Al-Saidi highlighted that Lebanon, Sudan, and Yemen are highly exposed and politically fragile in the food sectors due to Russia and Ukraine wars. This resulted in the inaccessibility of food and nutrition in the Gulf countries. The authors outlined the immediate response to strengthening sustainable agriculture, enhancing storage capacities, and grain procurement strategies from international suppliers to mitigate the food crisis.

A community-based study on the Productive SafetyNet program in the South Gondar Zone of Northwest Ethiopia was accomplished by Engidaw et al., where authors underlined that the infants from households with Productive SafetyNet users had a low minimum acceptable diet which is interlinked with marital status, father's educational status, child age, wealth index and place of delivery.

The cultivators of the South East Asian region are low in essential amino acids, particularly lysine and tryptophan content. Kaur et al. analyzed physical characteristics, proximate composition and flat bread (chapatti) making quality among seven genotypes comprising two QPM hybrids, two normal maize hybrids and three normal white maize landraces. The result showed that Landrace 593 has the highest protein and ash content, PMH 10 and IQMH 203 exhibited the highest and lowest hydration index, respectively. In contrast, two QPM hybrids showed significantly higher lysine and tryptophan content than other genotypes. Additionally, concerning chapatti making, QPM hybrids were identified as promising materials with improved nutritional quality.

This Research Topic will provide an overview of the present scenario on food security and potential adaptation in response to the global food crisis.

Author contributions

SC: Conceptualization, Writing – review & editing. AN: Writing – original draft. GS: Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Co-implementation of conservation tillage and herbicides reduces weed and nematode infestation and enhances the productivity of direct-seeded rice in North-western Indo-Gangetic Plains

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Direct-seeded rice (DSR) can be a resource-efficient alternative to puddled transplanted rice (PTR), but weeds and nematodes pose severe challenges. Conservation agriculture (CA)-based DSR may inhibit/influence weeds/nematodes, which can be further intensified by adopting better weed control. Hence, this experiment was undertaken. Five CA-based DSR practices involving zero tillage, residue retention, brown manuring, and superimposed with four weed control/herbicide options were compared with PTR in a split-plot design replicated three times. All DSRs encountered more weeds and plant parasitic nematodes (PPNs) than PTR. Root-knot nematodes (RKN) infested five among 14 weeds present in rice and was first time found in *Dinebra retroflexa*. A CA-based zero till (ZT)DSR+ mungbean residue – ZT wheat + rice residue – ZT mungbean+wheat residue system reduced weeds significantly. It reduced RKN galls in *Echinochloa colona, Echinochloa crusgalli,* and rice plants by 72, 58, and 56%, respectively. In soil too, RKN and other PPNs, namely, *Tylenchorhynchus brevilineatus* and *Pratylenchus thornei* were reduced by 39%, 32%, and 26%, respectively, which gave a 6.3–22.7% higher yield in this CA practice than other DSRs. Pyrazosulfuron-ethyl, cyhalofop-butyl, and bispyribac-Na applied sequentially reduced weeds and PPNs, increased rice yield by 176.1%, and were at below detectable levels in soil, rice grains, and straw, and were safe for rotational crops. The above

ZT-based triple cropping with residue supplemented with herbicides through better weed and nematode control would be an alternative to PTR in the North-wester Indo-Gangetic Plains of India and in similar agroecologies of the tropics/sub-tropics. This study would help farmers and policymakers to design integrated weed and nematode management modules using tillage, crop residue, and herbicides/pesticides for higher DSR yield and income.

KEYWORDS

bispyribac-Na, cyhalofop-butyl, LC-MS/MS, plant parasitic nematodes, QuEChERS, root-knot nematode, *Sesbania* brown manuring, grain yield

Introduction

Recently, the sustainability of puddled transplanted rice (PTR)–conventional till wheat (CTW) cropping system, the most dominant system practiced in nearly 10.5 million ha in the Indo-Gangetic Plains (IGP) of India (Ladha et al., 2009; Das et al., 2018) is threatened due to a host of problems, mainly associated with PTR. PTR is less labor-, water-, time-, energy-, and carbon-efficient and more cost-intensive (Gupta et al., 2016; Nawaz et al., 2017b; Raj et al., 2017; Das et al., 2020b; Sen et al., 2021). Puddling done in PTR affects soil structures and reduces subsurface permeability by forming hard pans (Mondal et al., 2019). PTR delays wheat sowing and can reduce 8–9% yield of wheat (Kumar and Ladha, 2011; Bhattacharyya et al., 2015). New resource-efficient and climate-smart management approaches are required to ensure food production in Indian IGP and make a substantial contribution to the food security of South-East Asia. Conservation Agriculture (CA) is a viable alternative to tillage-intensive agriculture (Kassam et al., 2018; FAO, 2020), which can improve biodiversity and above- and below-ground biological processes (Ghosh et al., 2019), and leads to higher use efficiencies of water and nutrients and sustainable crop production (FAO, 2020). Direct-seeded rice (DSR) is an alternate rice production technology and can be a potential alternative to PTR (Farooq et al., 2011; Kumar and Ladha, 2011). Under CA, zero till DSR (ZTDSR) is adopted in the rice–wheat system. The ZTDSR – ZT wheat (∼ZTW) system with residue has advantages over transplanting: earlier rice maturity, lower water (Nawaz et al., 2017b; Mohammad et al., 2018) and labor requirement, timely/early sowing of wheat, and higher economic returns (Bhattacharyya et al., 2015; Nawaz et al., 2017b; Raj et al., 2017). But DSR is heavily infested with weeds and nematodes, irrespective of climates and soils due to changes in ecology (Rao et al., 2007; Kyndt et al., 2014; Chauhan et al., 2015; Khan, 2015). DSR yield loss due to weeds varies across locations depending on management practices (Chauhan and Opena, 2012; Raj et al., 2016). It could be even 100% in a certain situation (Awan et al., 2015). Globally, the potential yield loss in rice due to various pests has been estimated to be around 77%, of which weeds contributed the highest 37.1% loss (Oerke, 2006). The losses caused by animal pests (insects, mites, nematodes, rodents, slugs/snails, birds, etc), pathogens, and viruses were 24.7, 13.5, and 1.7%, respectively. In India, the actual economic loss in rice due to weeds is 4,420 million US$ annually, the highest among the losses caused by 10 major crops (Gharde et al., 2018). The ZTDSR, residue retention, and brown manuring (Nawaz et al., 2017a; Behera et al., 2018; Behera and Das, 2019; Das et al., 2020a) crop intensification with a legume (Das et al., 2020b) highly influences dominance and diversity of weeds by altering weed seeds recruitment/dispersal across the depth of soil (Chauhan and Opena, 2012; Chauhan et al., 2015). In a long-term experiment, the conventional tilled DSR (∼CTDSR) - ZTW system was followed for the first 4 years (from 2010 to 2013), and weed management was studied in CTDSR in 3rd and 4th years (2012 and 2013). The experiment was fully modified to a CA system with three principles (Kassam et al., 2018) by adopting ZTDSR with residue in 2014, which led to a weed shift to annual grassy weeds [*Dactyloctenium aegyptium* (L.) Willd., *Dinebra retroflexa* (Vahl) Panz., and *Leptochloa chinensis* (L.) Nees], and perennial sedges (*Cyperus esculentus* L., *Cyperus rotundus* L.). Bispyribac-Na (hereafter referred to as bispyribac) recommended could not control these weeds. This prompted us to design this experiment in 2018 (9th year) and 2019 (10th year) to evaluate afresh weed control practices in ZTDSR and their associated effects on nematodes. Newer herbicides and combinations, such as the sequential applications of pre-emergence pyrazosulfuron-ethyl (hereafter referred to as pyrazosulfuron) as a substitute of pendimethalin, followed by (∼fb) post-emergence bispyribac and cyhalofop-butyl (hereafter referred to cyhalofop) as supplementary to bispyribac, were studied to control weed better and prevent/arrest weed dynamics. Pendimethalin, a broad-spectrum, but a grass-killer exclusively pre-emergence herbicide inhibits microtubule assembly in cell division (Das and Das, 2018). Pyrazosulfuron is a pre-emergence, broad-spectrum herbicide and inhibits acetolactate synthase (∼ALS). Bispyribac is also a broad-spectrum herbicide, inhibiting ALS, but post-emergence and less effective against certain grassy weeds (Sen et al., 2021). Cyhalofop-butyl is an acetyl coenzyme A carboxylase (ACCase) inhibitor herbicide, post-emergence, and kills exclusively grassy weeds.

Recently, there has been a considerable increase in plant-parasitic nematodes (PPNs) in crops worldwide (Mantelin et al., 2017; Devaraja et al., 2018). The changes in agroecology, tillage, and management practices influenced nematodes' community/species structure and their interactions with hosts (Kyndt et al., 2014; Pankaj et al., 2015; Liu et al., 2019). The PPNs can reduce rice yield by 10–25% (Bridge et al., 2005) or even more based on location and initial inoculum level (Ornat and Sorribas, 2008). Worldwide annual economic losses due to nematodes in crops are estimated to be US$ 173 billion (Elling, 2013). Kumar et al. (2020) reported that PPNs caused 21.3% crop losses amounting to US$ 1.58 billion per year in India. The economic loss in rice crops due to root-knot nematode (*Meloidogyne graminicola* Golden & Birchfield) alone was INR 23.3 billion (US$ 0.29 billion) annually. Among the top 10 PPNs of the world, root-knot nematode (RKN), cyst nematode (*Heterodera oryzae* Luc & Berdon), root-lesion nematode (*Pratylenchus thornei* Sher and Allen), and rice white-tip nematode (*Aphelenchoides besseyi* Christie) can cause damage to rice (Jones et al., 2013).

Several researchers (Chauhan and Opena, 2012; Chauhan et al., 2015; Abbas et al., 2019; Pandey and Kandel, 2020; Sen et al., 2021) have reported variable effects of the varying combinations of tillage, crop residue, and herbicides on weeds in DSR across locations. Puddling could significantly reduce nematodes in PTR, while nematodes such as RKN, *Meloidogyne triticoryzae*, and *Tylenchorhynchus mashoodi* were higher in DSR (Gaur and Singh, 1993; Chandel et al., 2002). Similarly, Suong et al. (2019) found higher root-parasitic nematodes in rice under direct-seeded mulch-based cropping system than in conventional plow-based tillage in Cambodia. The populations of *Tylenchorhynchus brevilineatus* and *Pratylenchus spp* were significantly higher in ZT than in CT fields (Pankaj et al., 2006). In contrast, Yadav et al. (2021) reported lesser RKN and PPNs in DSR than in PTR. However, the effect of herbicides on nematodes is less/negligibly studied. Zhang et al. (2010) highlighted that acetochlor and carbofuran reduced total nematodes and PPN in soybean. Weeds act as alternate hosts of these PPNs in the presence/absence of crops and are sources of inoculums for the next crops (Rich et al., 2009; Baghel et al., 2020). All these studies having combinations of tillage, residue, crop rotation, herbicides, etc. were different leading to variable effects on weeds and nematodes. In fact, the CA effect is location-specific, depending on soil type, prevailing climate, weed and nematode species distribution, etc., which suggests that studies need to be carried out to validate its impact on these pests across locations. There are gaps in location-specific comprehensive studies encompassing tillage (ZT and CT), nature/kind and amount of residue (cereal, legume, and brown manure crop residue), cropping (double or triple cropping with legume intervention), herbicides rotation (arresting weed dynamics) on weeds, and PPNs, especially RKN (most devastating to rice). Identifying new emerging weeds as alternate hosts of these nematodes in rice is also lacking. This provides opportunities for multidisciplinary integrated weed and nematode management research in DSR involving CA and weed management/herbicides. We hypothesized that the CA-based DSR supplemented with herbicides may lead to better weed and nematode management. The objectives were: to evaluate CA and weed management/herbicides' effects on weeds, nematodes, and productivity of rice; and to develop an effective weed management strategy for DSR under a CA-based rice–wheat system.

Materials and methods

Experimental sites and treatments

Experiments were conducted in the 9th (∼2018) and 10th (∼2019) years of a long-term conservation agriculture (CA)-based rice–wheat system (mentioned in Section Introduction) at ICAR-Indian Agricultural Research Institute, New Delhi (28°35′ N; 77°12′ E; 228 m above mean sea level). Six main plot treatments, involving tillage and crop residue, and four sub-plot treatments involving weed control/herbicides (Table 1) were laid out in a split-plot design with three replications. A triple cropping system involving a legume crop mungbean, which is usually not followed by the farmers, was taken as a treatment for comparison with the CA-based double cropping systems and conventional PTR–CTW system. Unweeded control (UWC) was a natural uninhibited weed infestation. The soil (order Inceptisol, Typic Haplustept) was clayey loam on the surface and loam below.

Crop sowing and agronomic practices

For ZTDSR, rice hybrid (Arize 6129 Gold) was sown by using a happy seeder with 25 kg seed ha^{-1} in rows 20 cm apart at 2–3 cm depth of soil. For PTR, transplanting was done manually at 20 cm × 10 cm spacing with 25 days old seedlings. For ZTW, wheat was sown by using a happy seeder in rows 20 cm apart at 3–5 cm depths of soil with 100 kg seed ha^{-1}. For triple cropping treatments, mungbean was sown after wheat harvest during summer using a happy seeder at 20 cm × 10 cm spacing. Recommended doses of 150 kg N, 26.2 kg P, and 33.1 kg K ha^{-1} were applied to rice and wheat. A 30% recommended dose of N and full doses of P and K were applied as basal, and the rest of N was applied in equal halves at active tillering and panicle initiation stages of rice and wheat. Diammonium phosphate at 100 kg ha^{-1} was applied to mungbean as basal.

TABLE 1 Treatments adopted in the experiment.

Treatment	Treatment short forms	Treatment code
Conservation agriculture practices (C)		
Zero-till (ZT) direct-seeded rice (DSR) – zero till wheat (ZTW)	ZTDSR-ZTW	C1
ZTDSR + wheat residue (WR)- ZTW + rice residue (RR)	ZTDSR + WR – ZTW+RR	C2
ZTDSR + WR + brown manuring (BM)- ZTW+RR	ZTDSR + WR+BM – ZTW+RR	C3
ZTDSR- ZTW-zero-till mungbean (ZTMB)	ZTDSR-ZTW-ZTMB	C4
ZTDSR + mungbean residue (MR) – ZTW + RR-ZTMB + WR	ZTDSR+MR-ZTW+RR-ZTMB+WR	C5
Puddled transplanted rice (PTR)- conventional till wheat (CTW)	PTR-CTW	C6
Weed control treatments (W)		
Unweeded control	UWC	W1
Pendimethalin at 1.5 kg ha^{-1} applied at 1 day after sowing (DAS) or 3 days after transplanting (DAT) as pre-emergence (PE) followed by (*fb*) post-emergence (PoE) bispyribac-Na at 0.025 kg ha^{-1} applied at 25 DAS/DAT	Pendi. *fb* bisp.	W2
Pyrazosulfuron-ethyl at 0.025 kg ha^{-1} as PE *fb* tank-mixture of cyhalofop-butyl at 0.100 kg ha^{-1} + bispyribac-Na at 0.025 kg ha^{-1} at 25 DAS (PoE)	Pyraz. *fb* cyhal. + bisp.	W3
Pyrazosulfuron-ethyl at 0.025 kg ha^{-1} as PE *fb* cyhalofop-butyl at 0.100 kg ha^{-1} at 20 DAS *fb* bispyribac-Na at 0.025 kg ha^{-1} at 25 DAS (PoE)	Pyraz. *fb* cyhal. *fb* bisp.	W4

Weeds density, rice yield, and economics

Two central rows of rice (~0.40 m) up to a length of 0.5 m were selected randomly from two locations in each plot. Weeds were collected, counted species-wise, and categorized into grassy, broad-leaved, and sedge weeds, which were summed up as total weeds. A net plot area comprising 16 rows of rice up to a length of 2.8 m (~3.2 m × 2.8 m) was harvested for grain yield recorded at 12% moisture. The common cost of all treatments was the sum total of the prevailing costs of inputs/operations such as seed, fertilizer, irrigation, plant protection (excluding herbicide), harvesting, and threshing. The cost of treatment constituted the costs of tillage (ZT/CT/puddling), sowing (DSR/nursery), transplanting, brown manuring, crop residue, and herbicide as applicable to the treatment. The common cost *plus* treatment cost constituted the total cost of treatment. Minimum support price for rice grains of the Government of India was used for calculating economics. Gross returns (GR), net returns (NR), and net benefit:cost (NB:C) were estimated as per Das and Das (2018). The exchange rates of November 2018 and 2019 were considered for converting Indian Rupees (~INR) to US$ (X-rates, 2017).

Nematodes population

Soil samples were collected from five locations in each plot using a tube auger (5-cm diameter) at 60 DAS. These five cores soils were composited and mixed thoroughly, and a sample core of 200 cc was taken in a polyethylene bag and washed. Then, muddy water suspension was poured on double-folded tissue paper superimposed on wire mesh placed on the top of the Petri dish and placed for incubation at 25°C−29°C for 48 h. In the second-stage juveniles (J2s), adult nematodes passing through the tissue paper to the Petri dishes having clear water suspension were observed under the stereoscopic binocular microscope. Ten J2s and adult nematodes were killed by mild heating and prepared temporary slides to identify nematode species (Pokharel et al., 2007). Standard procedures were followed for determining nematode populations (Southey, 1986), root-knot nematode galls in rice and weed plants (Coyne et al., 2007), and gall index (Pederson and Windham, 1989).

Herbicide residue estimation in rice grains and straw and soil

Residues of bispyribac, cyhalofop, pendimethalin, and pyrazosulfuron in rice grains, straw, and soil were estimated using QuEChERS (Quick, Easy, Cheap, Effective, Rugged, and Safe) method and subsequent analysis by liquid chromatography-mass spectroscopy/mass spectroscopy (LC-MS/MS) (Schenck and Hobbs, 2004).

Extraction and cleanup of herbicides from rice grains and soil

Soil and rice grains at harvest were collected from each treatment and their representative samples (100 g each) were prepared by quartering. Rice grains were homogenized in a mixer grinder, and soil samples were dried, ground by pestle mortar, and sieved through a 2-mm sieve. An aliquot of 5 g

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each for grains and soil was taken in 50 ml centrifuge tubes separately. Then, 2.5 ml of water was added to it and kept for half an hour. After that, 5 ml of acetonitrile, 2 g of anhydrous magnesium sulfate, and 0.75 g of NaCl were added into the centrifuge tube and were mixed thoroughly with a vortex mixer for 2 min. It was then centrifuged at 5,000 RPM for 5 min at a temperature of 27±1°C. After centrifugation, 1 ml of supernatant was taken in a 1.8 ml microcentrifuge tube and subjected to cleanup by dispersive solid-phase extraction using primary secondary amine (PSA) sorbent (50 mg) and anhydrous magnesium sulfate (150 mg) and vortexed for 1 min. It was then centrifuged for 5 min at 5,000 RPM in a microcentrifuge. After clean-up, the supernatant extract was filtered through a syringe filter (0.22 µm) and analyzed in LC-MS/MS.

Extraction and cleanup of herbicides from rice straw

Representative samples of rice straw (100 g) prepared by quartering were homogenized in a Willy mill straw crusher. An aliquot of 2.5 g was taken in a 50-ml centrifuge tube and 2.5 ml of water was added to it and kept for half an hour. Then, 20 ml of acetonitrile, 1 g of anhydrous magnesium sulfate, and 250 mg of NaCl were added to the centrifuge tube and were mixed thoroughly with a vortex mixer for 2 min. It was centrifuged at 5,000 RPM for 5 min at a temperature of 27±1°C. After centrifugation, 4 ml of supernatant was taken, which was evaporated to dryness by a rotary vacuum evaporator and reconstituted with 1 ml of acetonitrile. The 1-ml reconstituted supernatant was taken in a 1.8-ml microcentrifuge tube and subjected to cleanup by dispersive solid-phase extraction using primary secondary amine (PSA) sorbent (50 mg) and anhydrous magnesium sulfate (150 mg) and vortexed for 1 min. It was then centrifuged for 5 min at 5,000 RPM in a microcentrifuge, and the supernatant extract was filtered through a syringe filter (0.22 µm) and analyzed in LC-MS/MS.

Instrumental analysis of herbicide residue

The LC-MS/MS method for identification and quantification of bispyribac, cyhalofop, pendimethalin, and pyrazosulfuron was developed through optimizing LC and MS instrumental parameters in the Shimadzu LCMS/MS-8030 instrument equipped with Zorbax Eclipse Plus C_{18} column (Agilent make) of dimension 3 mm i.d., 10 cm length with 3.5 µm column coating. In electrospray ionization (ESI) with positive mode having DL temperature of 250°C, heat block temperature of 400°C, nebulizing gas flow of 3 ml/min, drying gas flow of 15 ml/min, multiple reaction monitoring (MRM) was optimized for selection of the best products for identification and quantification of each herbicide. The MRM optimization parameters, i.e., collision energy (CE), Q1 pre-bias and Q3 pre-bias, dwell time, and pause time for each event, were

TABLE 2 LC-MS/MS quantifier and qualifier MRM transitions with regression equation of the herbicides.

SN.	Herbicide	Molecular weight (g/mol)	Molecular ion *m/z*	Retention time (min)	Quantifier ion transition (Q1)	Qualifier ion transition (Q2)	Qualifier ion transition (Q3)	Regression equation	Correlation coefficient (r)
1.	Bispyribac-sodium	452.3	430.65 $(M - Na + H)^+$	2.27	430.65 > 274.90	430.65 > 118.90	430.65 > 412.95	Y = 1.84009e + 006x + 44,777.8	+0.9987
2.	Cyhalofop-butyl	357.4	374.75 $(M + NH_4)^+$	3.32	374.75 > 255.90	374.75 > 120.00	374.75 > 357.95	Y = 1.67611e + 006x-140.639	+0.9993
3.	Pendimethalin	281.31	281.90 $(M + H)^+$	4.81	281.90 > 211.80	281.90$(M + H)^+$ 42.95	281.90 > 193.86	Y = 2.40925e + 006x-11,325.0	+0.9999
4.	Pyrazosulfuron-ethyl	414.4	415.10 $(M + H)^+$	2.24	415.10 > 182.10	-	-	Y = 2.06887e + 006x + 31,502.6	+0.9980

optimized according to the sensitivity of the compound. The mobile phase 10:90 water (5mM ammonium formate): methanol was used for eluting these four herbicides in the 6-min run and the flow of solvent was maintained at 0.2 ml/min. Herbicide standards in the concentration range of 0.1 to 1.0 ppm were injected to obtain a 5-point linearity curve within the detection range. As per the sensitivity of the analytes, the Limit of Detection [LOD] of the herbicides was found to be 0.01 μg/ml (signal: noise ratio ≥3:1), and the Limit of Quantification [LOQ] was found to be 0.05 μg/ml (signal: noise ratio ≥10:1). From the C_{18} column in 6 min run time, the retention time (RT) of bispyribac, cyhalofop, pendimethalin, and pyrazosulfuron were found to be 2.27, 3.31, 4.81, and 2.24 min, respectively (Table 2). The most intense MRM transition of each herbicide was designated as quantifier ion transition and used for quantification of the herbicides through Chrome Browser software associated with LC-MS/MS using system generated calibration curve (Figure 1). The quantifier MRM transitions were *m/z* 430.65>274.90 for bispyribac; *m/z* 374.75>255.90 for cyhalofop; *m/z* 281.90>211.80 for pendimethalin; and *m/z* 415.10>182.10 for pyrazosulfuron, respectively. Other less intense MRM transitions were used as qualifier ion transitions.

Recovery study

For the recovery of bispyribac, cyhalofop, pendimethalin, and pyrazosulfuron, herbicide-free rice grains, straw, and soil were fortified with 0.05 mg/kg (∼0.05 ppm) of the respective herbicide and analyzed following the above-mentioned procedure. The recoveries of bispyribac, cyhalofop, pendimethalin, and pyrazosulfuron were 86.6, 118.3, 72.8, and 87.5% (from soil); 62.5, 81.9, 78.5, and 113.9% (from grains); and 57.6, 114.2, 71.6, and 77.6% (from straw), respectively. All the recoveries of herbicides from the soil, grains, and straw were in the acceptable range of 70–120%, except the recovery of bispyribac, which was relatively lower from rice grains and straw.

Statistical analysis

Data on weed, nematode, and rice were analyzed by the analysis of variance (ANOVA) technique for a split-plot design using PROC GLM in SAS 9.3 (SAS Institute, Cary, NC). Weed and nematode populations were transformed through the square-root method [$(x+0.5)^{½}$] before ANOVA to reduce higher variation. The species-wise populations of weeds and nematodes and rice grain yield were subjected to Levene's test for homogeneity of variance. The error variances for almost all parameters (i.e., weed and nematode population, rice grain yield) were homogeneous over the years, indicating that the uniformity in error variance was significant. Hence, pooled analysis was done to find out the effects of the year (Y), and interactions between Y × conservation agriculture (C), Y × weed control (W), C × W, and Y × C × W on the studied variables of weed, nematode and rice, and data are presented year-wise. The significance of treatment means was appraised using Tukey's honest significant difference (HSD) test at $p \leq .05$.

Results

Effects on weeds diversity, dynamics, and interference

A total of 14 weeds (Table 3), comprising six grassy (Table 4), four broad-leaved (∼BLW) (Table 5), and four sedge weeds (Table 6) were observed in rice under UWC. The pooled ANOVA reflected the significant difference between the years in densities of eight weeds, namely, *Echinochloa colona* (L.) Link., *Dactyloctenium aegyptium* (L.) Willd., *Dinebra retroflexa* (Vahl) Panz., *Leptochloa chinensis* (L.) Nees, *Eclipta alba* L., *Trianthema portulacastrum* L., *Cyperus esculentus* L. and *Cyperus difformis* L. weeds with higher densities in the second year than in the 1st year. In contrast, there was no significant yearly difference in the densities of the rest of the six weeds, namely, *Echinochloa crusgalli* (L.) Beauv*, Eleusine indica* (L.) Gaertn., *Phyllanthus niruri* L., *Alternanthera philoxeroides* (Mart.) Griseb*, Cyperus rotundus* L. and *Cyperus iria* L. (Table 3). The pooled mean effect of CA and weed control practices and their interactions were significant for all 14 weeds observed in rice (Table 3). The DSRs encountered higher infestations of *Echinochloa colona*, *Dactyloctenium aegyptium*, *Dinebra retroflexa*, *Leptochloa chinensis*, and *Eleusine indica* than the PTR, which, on the contrary, had a higher density of *Echinochloa crusgalli* (Table 4). The triple ZT system with three crops residue (C5) among the DSRs (C1-C5) led to the lowest densities of *D. aegyptium, D. retroflexa and L. chinensis.* PTR (C6) system was not infested with these weeds but had the highest density of *E. crusgalli*. Broad-leaved weeds *Eclipta alba*, *Phyllanthus niruri*, and *Trianthema portulacastrum* infested DSRs (C1-C5) but not PTR (C6) except *E. alba* in 2019 (Table 5). *Eclipta alba* decreased while *T. portulacastrum* increased (in C4&C5) in the second year under DSRs. The C5 caused a significant reduction of these weeds compared to C4, having the highest densities. *Alternenthera philoxeroides* were found in C6 and C1, the former having a significantly higher density than the latter. Perennial sedges *Cyperus esculentus* L. and *Cyperus rotundus* L. had larger densities in CA-based DSRs (C1-C5) and were absent in PTR (C6), whereas annual sedges *Cyperus difformis* L., *Cyperus iria* L. were observed in PTR and absent in DSRs in both the years (Table 6). Among DSRs, C4 had the highest densities of *C. esculentus and C. rotundus.* The pyrazosulfuron *fb* cyhalofop *fb* bispyribac treatment resulted in significantly lower densities of all grassy weeds except *E. indica* (Table 4) and all broad-leaved

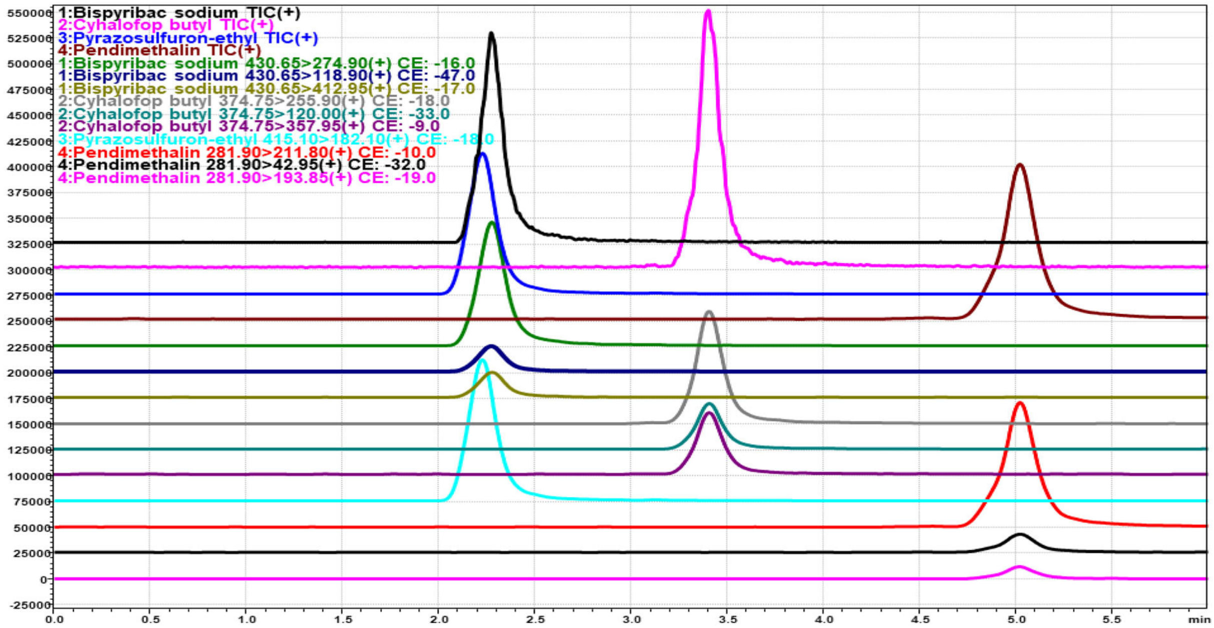

FIGURE 1
Base shift chromatogram showing multiple reaction monitoring (MRM) transition of bispyribac sodium, cyhalofop-butyl, pyrazosulfuron-ethyl, and pendimethalin herbicides.

weeds than UWC and pyrazosulfuron *fb* tank-mix cyhalofop + bispyribac (Table 5). This herbicide treatment also led to lower densities of *C. esculentus, C. rotundus, C. difformis, and C. iria* than other treatments in both years (Table 6).

Effects on species-wise and total nematodes

RKN galls were found in four grassy weeds (*E. colona, E. crusgalli, D. retroflexa, E. indica*) and one broad-leaved weed (*E. alba*) among 14 weeds present in this study. CA significantly influenced RKN galls in weeds and rice. RKN galls were significantly higher in *E. colona, E. crusgalli,* and rice in CA-based DSRs than PTR-CTW (Table 7). Among DSRs, the brown manuring (C3) had the highest, whereas the triple ZT with three crops residue (C5) had the lowest RKN galls and gall index (GI) of *E. colona, E. crusgalli,* and rice. The C5 led to reduction in RKN galls by 72, 60, 68, and 58% in *E. colona*; 58, 57, 52, and 34% in *E. crusgalli*; and 56, 50, 48, and 27% in rice compared to C3, C1, C2, and C4, respectively. CA practices also significantly influenced plant parasitic nematodes (PPNs) (Table 9). DSRs had higher densities of RKN, *T. brevilineatus* and *P. thornei* than PTR, which, on the contrary, had higher *H. oryzeae*. The C5 led to a reduction in RKN by 30% and *T. brevilineatus* by 27% compared to C3 and had the lowest total PPNs (mean of 2 years). Contrarily, C1 had significantly higher total PPNs (Table 9) than other treatments. The application of pyrazosulfuron *fb* cyhalofop *fb* bispyribac led to a reduction in RKN galls by 73.7% in rice plants by reducing weed density by 82.6% and had significantly lower RKN galls in rice than in other treatments (Table 8). Also, this had the lowest total PPNs (Table 9). It could reduce RKN, *T. brevilineatus, P. thornei*, and *H. oryzeae* by 27%, 71%, 82%, and 53% during 2018 and 19%, 65, 81, and 47% during 2019, respectively, compared to UWC. The RKN galls of weeds (∼*E. colona, E. crusgalli*) and rice plants (Figures 2A,B) were significantly ($p \leq .01$) positively correlated (r = 0.88**, 0.89**; R^2 = 0.78, 0.79, respectively; n = 18), but the relationship was inverse (Figures 3A,B) between PPNs and rice grain yield [r = −0.745** (2018); r = −0.827**(2019), n = 72].

Effects on rice grain yield and economics

Pooled ANOVA revealed that the mean effects of year, CA, and weed control practices, and their interactions (namely, Y×W; C×W) on rice grain yield were significant (Table 3). Rice grain yield was significantly higher in the 1st year (2018) than in the 2nd year (2019) (Table 10). Conventional PTR (C6) resulted in significantly higher rice yield than any DSRs (C1-C5) (Table 10). Among DSRs, the triple ZT system with three crops residue (C5) was most superior with 6.3, 22.4, 22.0, and 21.0% higher yield in 2018, and 13.1, 17.8, 22.1,

TABLE 3 Pooled analysis of variance (ANOVA) of *Echinochloa colona, Echinochloa crusgalli, Dactyloctenium aegyptium, Dinebra retroflexa, Leptochloa chinensis, Eleusine indica, Eclipta alba, Phyllanthus niruri, Alternanthera philoxeroides, Trianthema portulacastrum, Cyperus esculentus, Cyperus rotundus, Cyperus difformis, Cyperus iria* and grain yield showing the effects of years, CA and weed control practices and their interactions.

Source of variation	DF	*E. colona*‡	*E. crusgalli*‡	*D. aegyptium*‡	*D. retroflexa*‡	*L. chinensis*‡	*E. indica*‡	*E. alba*‡	*P. niruri*‡	*A. philoxeroides*‡	*T. portulacastrum*‡	*C. esculentus*‡	*C. rotundus*‡	*C. difformis*‡	*C. iria*‡	*Grain yield*
Year (Y)	1	67.88**	1.25	35.73**	14.00**	17.20**	2.06	42.65**	0.11	0.86	26.76**	10.67**	3.91	28.66**	1.62	86.02**
Replication within year	4	1.73	0.21	0.82	1.60	0.55	1.77	1.84	0.85	0.64	1.32	0.56	0.40	0.58	1.79	6.74**
CA practice (C)	5	64.75**	35.98**	114.81**	181.13**	56.64**	11.81**	38.85**	189.79**	99.97**	263.15**	452.08**	69.41**	783.32**	155.29**	73.16**
Y × C	5	1.37	4.56**	2.20	1.10	18.31**	4.75**	20.96**	8.61**	3.39*	11.07**	6.01**	1.39	28.66**	1.62	1.18
Error (a)	20	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Weed control practice (W)	3	296.36**	517.85**	93.56**	230.98**	37.30**	5.48**	347.45**	168.34**	53.92**	588.51**	67.79**	27.99**	26.77**	15.43**	1347.36**
Y × W	3	10.00**	24.21**	5.74**	2.95*	3.31*	33.83**	7.23**	9.55**	19.06**	25.03**	0.82	0.01	2.78*	0.41	13.94**
C× W	15	11.16**	14.41**	5.30**	14.05**	5.57**	22.51**	7.55**	23.20**	24.35**	246.22**	7.27**	1.93*	26.77**	15.43**	9.61**
Y × C × W	15	0.63	8.30**	1.01	0.59	3.03**	5.51**	7.15**	7.71**	14.41**	10.36**	0.49	0.16	2.78**	0.41	1.78
Error (b)	72	-	-	-	-	-		-	-	-	-	-	-	-	-	-

*Significant at p ≤.05; **Significant at p ≤.01; ‡Transformed data through square-root ($\sqrt{(x+0.5)}$) method.

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TABLE 4 Species-wise grassy weeds density (no. m^{-2}) in rice as influenced by CA and weed control treatments at 60 DAS/DAT during 2018 and 2019.

Treatment	Grassy weeds density (no. m^{-2})‡											
	Echinochloa colona		*Echinochloa crusgalli*		*Dactyloctenium aegyptium*		*Dinebra retroflexa*		*Leptochloa chinensis*		*Eleusine indica*	
	2018	2019	2018	2019	2018	2019	2018	2019	2018	2019	2018	2019
CA practices (C)												
ZTDSR-ZTW (C1)	4.5^{a†}	5.2^{a}	1.8^{b}	1.8^{b}	3.3^{a}	3.8^{a}	4.3^{a}	4.4^{a}	2.4^{a}	3.3^{a}	0.9^{b}	1.2^{abc}
ZTDSR + WR –ZTW + RR (C2)	3.4^{b}	4.5^{ab}	2.0^{ab}	2.0^{ab}	2.7^{b}	3.5^{a}	3.8^{b}	4.2^{a}	2.5^{a}	2.8^{a}	0.8^{b}	1.3^{a}
ZTDSR + WR+BM – ZTW+RR (C3)	3.1^{bc}	4.4^{ab}	1.8^{b}	1.4^{bc}	2.6^{b}	3.2^{a}	3.7^{b}	4.0^{ab}	2.4^{a}	0.7^{b}	0.7^{b}	1.0^{abc}
ZTDSR-ZTW-ZTMB (C4)	2.8^{c}	3.4^{bc}	1.3^{c}	0.7^{c}	2.7^{b}	3.1^{ab}	2.6^{c}	3.1^{bc}	1.8^{ab}	0.7^{b}	0.9^{b}	0.8^{bc}
ZTDSR+MR-ZTW+ RR-ZTMB +WR (C5)	1.7^{d}	2.6^{c}	1.3^{c}	1.3^{bc}	2.1^{b}	2.4^{b}	2.1^{d}	2.7^{c}	1.5^{b}	0.7^{b}	1.7^{a}	1.3^{ab}
PTR-CTW (C6)	2.2^{d}	2.6^{c}	2.3^{a}	2.8^{a}	0.7^{c}	0.7^{c}	0.7^{e}	0.7^{d}	0.7^{c}	0.7^{b}	0.7^{b}	0.7^{c}
Weed control treatments (W)												
UWC (W1)	5.4^{a}	7.2^{a}	4.4^{a}	3.4^{a}	3.0^{a}	3.6^{a}	4.2^{a}	4.7^{a}	2.4^{a}	1.7^{ab}	1.1^{a}	2.0^{a}
Pendi. *fb* bisp. (W2)	1.9^{c}	2.7^{c}	0.9^{b}	1.1^{bc}	2.0^{b}	2.8^{b}	2.4^{c}	2.8^{c}	1.7^{b}	1.4^{b}	0.8^{a}	0.7^{b}
Pyraz. *fb* cyhal. + bisp. (W3)	3.1^{b}	4.2^{b}	1.0^{b}	1.5^{b}	2.8^{a}	3.2^{a}	3.2^{b}	3.6^{b}	2.1^{a}	1.8^{a}	1.1^{a}	0.7^{b}
Pyraz. *fb* cyhal. *fb* bisp. (W4)	1.3^{d}	1.2^{d}	0.7^{b}	0.7^{c}	1.6^{b}	1.6^{c}	1.7^{d}	1.6^{d}	1.4^{b}	1.1^{c}	0.8^{a}	0.8^{b}

‡Transformed data through square-root $(x+0.5)^{½}$ method before analysis of variance (ANOVA); † Within a column, the means followed by different lowercase letters are significantly different at $p \leq .05$ as per Tukey's HSD test.

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TABLE 5 Species-wise broad-leaved weeds density (no. m^{-2}) in rice as influenced by CA and weed control treatments at 60 DAS/DAT during 2018 and 2019.

Treatment	Broad-leaved weeds density (no. m^{-2})‡							
	Eclipta alba		*Phyllanthus niruri*		*Alternanthera philoxeroides*		*Trianthema portulacastrum*	
	2018	2019	2018	2019	2018	2019	2018	2019
CA practices (C)								
ZTDSR-ZTW (C1)	$1.9^{b\dagger}$	1.7^{b}	1.9^{b}	1.7^{b}	1.2^{b}	1.4^{b}	0.7^{c}	0.7^{c}
ZTDSR + WR –ZTW + RR (C2)	2.6^{b}	1.5^{bc}	1.6^{b}	1.9^{b}	0.7^{b}	0.7^{c}	0.7^{c}	0.7^{c}
ZTDSR + WR+BM – ZTW+RR (C3)	2.2^{b}	1.0^{c}	0.7^{c}	0.7^{c}	0.7^{b}	0.7^{c}	0.7^{c}	0.7^{c}
ZTDSR-ZTW-ZTMB (C4)	4.0^{a}	2.5^{a}	2.7^{a}	3.2^{a}	0.7^{b}	0.7^{c}	1.3^{a}	1.6^{a}
ZTDSR+MR-ZTW+ RR-ZTMB +WR (C5)	2.4^{b}	1.8^{b}	1.7^{b}	1.1^{c}	0.7^{b}	0.7^{c}	1.1^{b}	1.4^{b}
PTR-CTW (C6)	0.7^{c}	1.9^{ab}	0.7^{c}	0.7^{c}	2.1^{a}	1.7^{a}	0.7^{c}	0.7^{c}
Weed control treatments (W)								
UWC (W1)	$3.6^{a\dagger}$	3.5^{a}	2.5^{a}	3.1^{a}	1.1^{ab}	1.6^{a}	0.7^{b}	0.7^{b}
Pendi. *fb* bisp. (W2)	1.7^{c}	1.0^{c}	1.1^{c}	0.9^{c}	0.9^{bc}	0.7^{c}	0.7^{b}	0.7^{b}
Pyraz. *fb* cyhal. + bisp. (W3)	2.7^{b}	1.8^{b}	1.8^{b}	1.5^{b}	1.4^{ab}	0.9^{b}	1.4^{a}	1.8^{a}
Pyraz. *fb* cyhal. *fb* bisp. (W4)	1.2^{d}	0.7^{c}	0.8^{c}	0.7^{c}	0.7^{c}	0.7^{c}	0.7^{b}	0.7^{b}

‡Transformed data through square-root $(x+0.5)^{1/2}$ method before analysis of variance (ANOVA); †Within a column, the means followed by different lowercase letters are significantly different at p ≤.05 as per Tukey's HSD test.

TABLE 6 Species-wise sedge weeds density (no. m^{-2}) in rice as influenced by CA and weed control treatments at 60 DAS/DAT during 2018 and 2019.

Treatment	Sedge weeds density (no. m^{-2})‡							
	Cyperus esculentus		*Cyperus rotundus*		*Cyperus difformis*		*Cyperus iria*	
	2018	2019	2018	2019	2018	2019	2018	2019
CA practices (C)								
ZTDSR-ZTW (C1)	$5.6^{c\dagger}$	5.8^{c}	3.0^{bc}	3.4^{b}	0.7^{b}	0.7^{b}	0.7^{b}	0.7^{b}
ZTDSR + WR –ZTW + RR (C2)	5.0^{c}	5.6^{c}	2.9^{c}	2.9^{b}	0.7^{b}	0.7^{b}	0.7^{b}	0.7^{b}
ZTDSR + WR+BM – ZTW+RR (C3)	4.7^{c}	4.2^{d}	3.0^{c}	3.0^{b}	0.7^{b}	0.7^{b}	0.7^{b}	0.7^{b}
ZTDSR-ZTW-ZTMB (C4)	10.1^{a}	11.8^{a}	4.2^{a}	5.0^{a}	0.7^{b}	0.7^{b}	0.7^{b}	0.7^{b}
ZTDSR+MR-ZTW+ RR-ZTMB +WR (C5)	7.0^{b}	7.6^{b}	3.5^{b}	3.9^{ab}	0.7^{b}	0.7^{b}	0.7^{b}	0.7^{b}
PTR-CTW (C6)	0.7^{d}	0.7^{e}	0.7^{d}	0.7^{c}	3.5^{a}	4.8^{a}	2.4^{a}	2.8^{a}
Weed control treatments (W)								
UWC (W1)	7.1^{ay}	7.5^{a}	3.6^{a}	3.9^{a}	1.4^{a}	1.9^{a}	1.1^{a}	1.3^{a}
Pendi. *fb* bisp. (W2)	5.0^{c}	5.1^{c}	2.5^{c}	2.7^{bc}	1.1^{c}	1.2^{b}	0.9^{bc}	1.0^{bc}
Pyraz. *fb* cyhal. + bisp.(W3)	6.0^{b}	6.3^{b}	3.1^{b}	3.4^{ab}	1.2^{b}	1.4^{b}	1.0^{ab}	1.1^{ab}
Pyraz. *fb* cyhal. *fb* bisp.(W4)	4.0^{d}	4.7^{c}	2.3^{c}	2.6^{c}	1.0^{d}	1.0^{b}	0.8^{c}	0.9^{c}

‡Transformed data through square-root $(x+0.5)^{1/2}$ method before analysis of variance (ANOVA); † Within a column, the means followed by different lowercase letters are significantly different at p ≤.05 as per Tukey's HSD test.

and 22.7% higher yield in 2019 than C1, C2, C3, and C4, respectively. Among the weed control practices, the application of pyrazosulfuron *fb* cyhalofop *fb* bispyribac led to a significant increase in the yield than W1, W2, and W3 during both years (Table 10). This treatment increased 2 years' mean grain yield by 176.1, 19.6, and 7.7% than UWC, pyrazosulfuron *fb* tank-mix cyhalofop+bispyribac, and pendimethalin *fb* bispyribac, respectively. This herbicide treatment had significant interaction with CA, leading to comparable rice yields in C5 and C6, which were significantly higher than in other DSRs combined with these herbicides treatment (Table 10). The conventional farmers' practice (PTR-CTW; C6) incurred a higher cost of production (Figure 4) than all DSRs (C1–C5). The C1, C2, C3, C4, and C5 led to a reduction in the cost of production by US$ 235, 201, 174, 235, and 229 ha^{-1}, respectively, compared to C6. The triple ZT system with three crops residue (C5) fetched comparable net returns with that of PTR-CTW and resulted in significantly higher net returns than those in the rest of the DSRs. The net

TABLE 7 Root-knot nematode (RKN) galls (no. plant^{-1}) and gall index (GI) in weeds *Echinochloa colona, Echinochloa crusgalli,* and rice crop under unweeded control at 60 DAS/DAT across the conservation agriculture practices (mean of 2 years).

Treatments	RKN galls density (no. plant^{-1})			RKN Gall index*		
	Echinochloa colona‡	*Echinochloa crusgalli*‡	Rice‡	*Echinochloa colona*	*Echinochloa crusgalli*	Rice
ZTDSR-ZTW (C1)	5.3 ^{b†} (29)#	5.4^{a} (30)	5.4^{a} (29)	3.3^{b}	3.3^{a}	3.3^{b}
ZTDSR + WR –ZTW + RR (C2)	6.6^{ab} (43)	4.8^{a} (24)	5.2^{a} (27)	4.0^{a}	3.3^{a}	3.3^{b}
ZTDSR + WR+BM – ZTW+RR (C3)	7.6^{a} (58)	5.5^{a} (31)	6.1^{a} (37)	4.0^{a}	3.3^{a}	4.0^{a}
ZTDSR-ZTW-ZTMB (C4)	5.0^{b} (25)	3.5^{ab} (12)	3.7^{b} (13)	3.0^{b}	2.7^{ab}	2.7^{c}
ZTDSR+MR-ZTW+ RR-ZTMB +WR (C5)	2.1^{c} (4)	2.3^{bc} (5)	2.7^{b} (7)	1.7^{c}	1.7^{b}	2.0^{d}
PTR-CTW (C6)	0.7^{d} (0)	0.7^{c} (0)	0.7^{c} (0)	0^{d}	0^{c}	0^{e}

‡Transformed data through square-root $(x+0.5)^{1/2}$ method before analysis of variance; #Figures in the parentheses are original/observed values; †Within a column, the means followed by different lowercase letters are significantly different at $p \leq .05$ as per Tukey's HSD test.*GI 0 = no galls, GI 1 = 1 or 2 galls, GI 2 = 3–10 galls, GI 3 = 11–30 galls, GI 4 = 31–100 galls, and GI 5=more than 100 galls plant^{-1}.

TABLE 8 Reduction in weed population (no. m^{-2}) and root-knot nematode (RKN) galls in rice plants (no. plant^{-1}) across the weed control/herbicides treatments at 60 DAS/DAT (Pooled mean of 2 years).

Weed control treatments	Weed population (no. m^{-2})	RKN galls in rice plants (no. plant^{-1})
UWC (W1)	235^{a†}	19^{a}
Pendi. *fb*bisp. (W2)	69^{c} (70.6%)‡	7^{c} (63.2%)‡
Pyraz. *fb* cyhal. + bisp. (W3)	127^{b} (46.0%)	9^{b} (52.6%)
Pyraz. *fb*cyhal. *fb*bisp. (W4)	41^{d} (82.6%)	5^{d} (73.7%)

† Within a column, the means followed by different lowercase letters are significantly different at $p \leq .05$ as per Tukey's HSD test.
‡ Values in the parentheses are per cent reduction compared to UWC.

benefit:cost (NB:C) was significantly higher due to C5 (1.80) than C6 (1.31) and other DSRs. Among herbicides/weed control treatments, the pyrazosulfuron fb cyhalofop fb bispyribac (W4) resulted in significantly higher net returns and NB:C than UWC and other herbicide treatments (Figure 4). This treatment (W4) obtained 10.2% higher net returns compared to pendimethalin fb bispyribac (W2), which is the farmers' herbicides/weed control practice adopted for rice in India.

Herbicides residue in soil and rice grains and straw

Residues of all four herbicides (i.e., bispyribac, cyhalofop, pendimethalin, pyrazosulfuron) in rice grains and straw, and at 0–15 cm and 15–30 cm depth of soil were below the detectable level (BDL), except the negligible residue of pendimethalin varying from 0.013 to 0.018 mg kg^{-1} observed in upper 0–15 cm soil (Table 11). Pendimethalin residue was slightly higher in ZT residue-retained DSRs than PTR.

Discussion

Weed dynamics and interference

Contrasting tillage and crop establishment practices followed for 8 years led to weed dynamics/diversity in rice. Under PTR, intensive tillage/puddling resulting in the deeper placement of weed seeds, and continuous standing water preventing weed germination, particularly of photoblastic weeds could reduce almost all weeds except *E. crusgalli*, which was higher in PTR due to its ecological preference for growing under stagnant water. On the contrary, ZTDSR (mean of five DSRs) had 83 and 56% higher weed density in 2018 and 2019, respectively, and higher densities of grassy weeds *E. colona*, *D. aegyptium*, *D. retroflexa,* and *L. chinensis* than PTR. Under negligible or no soil disturbance, the ZT plots had more weed seeds on the soil surface, particularly of small-seeded grassy weeds. Ample sunlight on the soil surface led to higher weed emergence (Chauhan and Opena, 2012), and their seed bank build-up (Mishra and Singh, 2012). A similar thing happened under the triple ZT system without residue (C4). Besides ZT, mungbean crop grown during summer provided a favorable microclimate through adequate moisture and lower/buffered soil temperature, promoting germination of annual broad-leaved weeds *E. alba*, *P. niruri,* and *T. portulacastrum* (Table 5), and sedges *C. esculentus* and *C. rotundus* (Table 6).

During summer (May and June), the C4 plot had a lower temperature at 0–5 and 5–15 cm soils (~30–34°C & 29–32°C, resp.) due to mungbean crop than the C1–C3 and C6 plots (44–52°C and 38–42°C, resp.) (Field experience). Higher 44–52°C temperature at 0–5 cm soil in latter plots (kept fallow during summer) led to little solarization and might prove lethal to many annual weed seeds and tubers of *C. esculentus* and *C. rotundus*. Webster (2003) reported that soil temperature of more than 45°C considerably reduced tuber viability of *C. esculentus* and *C. rotundus*, and *C. esculentus* tubers were more sensitive to heat than C. *rotundus* tubers. Crops residue

TABLE 9 Plant parasitic nematodes (PPN) population (no. 200 cc soil^{-1}) across CA and weed control treatments in rice at 60 DAS/DAT during 2018 and 2019.

Treatment	*M. graminicola*‡		*T. brevilineatus*‡		*P. thornei*‡		*H. oryzeae*‡		Total PPN	
	2018	2019	2018	2019	2018	2019	2018	2019	2018	2019
CA practices (C)										
ZTDSR-ZTW(C1)	15.8†	18.7[b]	17.7[a]	19.6[a]	14.4[a]	16.5[a]	1.7[b]	1.9[b]	29.0[a]	33.1[a]
ZTDSR + WR – ZTW+RR(C2)	14.1[bc]	17.3[bc]	13.9[c]	15.6[c]	4.1[b]	4.8[b]	1.2[b]	1.3[b]	21.1[cd]	25.0[b]
ZTDSR + WR+BM – ZTW+RR(C3)	18.2[a]	20.8[a]	14.6[bc]	16.3[bc]	2.5[c]	3.3[c]	0.70[b]	0.7[b]	23.9[b]	27.3[b]
ZTDSR-ZTW-ZTMB (C4)	13.6[cd]	16.8[cd]	17.1[ab]	18.7[ab]	4.1[b]	4.8[b]	1.4[b]	1.5[b]	23.3[bc]	27.0[b]
ZTDSR+MR-ZTW+RR-ZTMB+WR(C5)	11.7[d]	15.4[d]	9.8[d]	12.5[d]	3.0[bc]	4.1[bc]	1.1[b]	1.2[b]	16.4[e]	21.3[c]
TPR-CTW(C6)	0.7[e]	0.7[e]	6.0[e]	8.1[e]	3.1[bc]	4.2[bc]	17.8[a]	18.5[a]	20.3[d]	22.4[c]
Weed control treatments (W)										
UWC (W1)	14.2[a]	16.5[a]	20.8[a]	22.4[a]	12.9[a]	15.5[a]	5.1[a]	5.1[a]	32.4[a]	35.8[a]
Pendi. *fb* bisp. (W2)	11.9[b]	14.6[c]	11.1[c]	13.5[b]	2.6[b]	3.2[b]	4.1[a]	4.4[ab]	19.3[c]	23.0[c]
Pyraz. *fb* cyhal. + bisp.(W3)	12.9[b]	15.4[b]	14.7[b]	16.7[b]	2.9[b]	3.5[b]	4.4[a]	4.5[a]	22.8[b]	26.2[b]
Pyraz. *fb* cyhal. *fb* bisp.(W4)	10.4[c]	13.3[d]	6.1[d]	7.9[c]	2.3[b]	3.0[b]	2.4[b]	2.7[b]	14.8[d]	19.0[d]

‡Transformed data through square-root $(x+0.5)^{1/2}$ method before analysis of variance; † Within a column, the means followed by different lowercase letters are significantly different at p ≤.05 as per Tukey's HSD test. *M. graminicola*, *T. brevilineatus*, *P. thornei*, *H. oryzeae are Meloidogyne graminicola*, *Tylenchorhynchus brevilineatus*, *Pratylenchus thornei*, *Hirschmanniella oryzeae*, respectively.

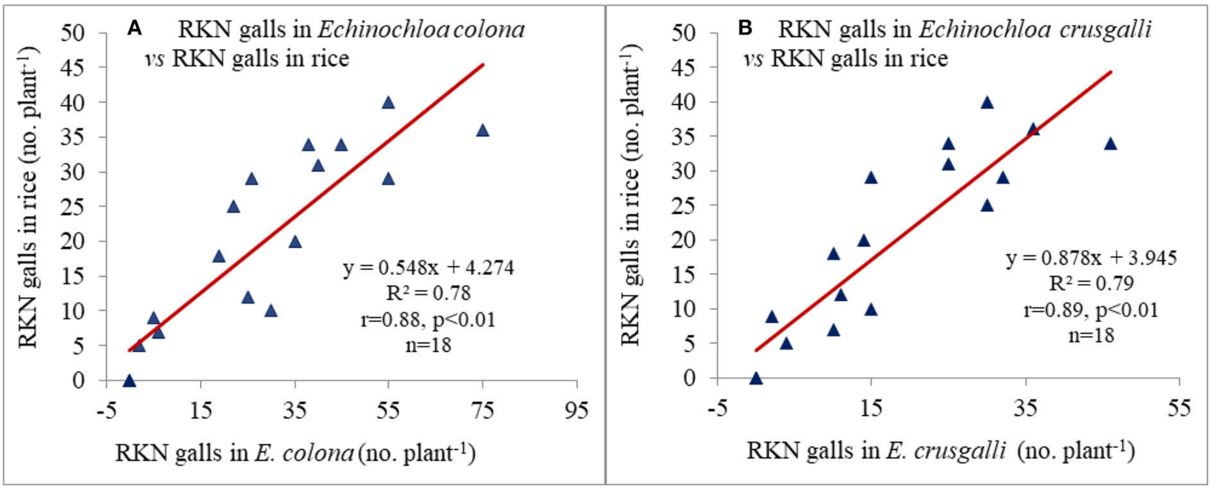

FIGURE 2
Relationship between root-knot nematode (RKN) galls in **(A)** *Echinochloa colona* and **(B)** *Echinochloa crusgalli* with RKN galls in rice (mean of 2 years).

also reduced weeds. Three crops (rice, wheat, and mungbean) residues under the mungbean-inclusive triple ZT system (C5) led to a considerable reduction in *C. esculentus* and *C. rotundus* (which were highly dominant in C4). The residue acts as a physical barrier to sunlight reducing weed germination and releasing allelo-chemicals into the soil (Jabran and Chauhan, 2015). Kumar et al. (2013) found that wheat residue suppressed *E. crusgalli, E. colona, D. aegyptium*, and *E. alba* in ZTDSR. Residue can also encourage weed seed foraging and predation actions by ants, insects, and birds and reduce surface seed bank.

Repeated weed flushes, crop stage-specific emergence of certain weeds, and new weed insurgence call for sound weed management in DSR (Jabran and Chauhan, 2015). In this study, ZT, residues (rice, wheat, mungbean, and brown manure crop *Sesbania*), and herbicides were adopted to pursue integrated weed management in DSR. The application of pyrazosulfuron *fb* cyhalofop *fb* bispyribac was most effective causing a significant reduction in densities of grassy, broad-leaved, and sedge weeds by 72, 60, and 43%, respectively (2-year mean). Pyrazosulfuron led to balanced control of early-emerging

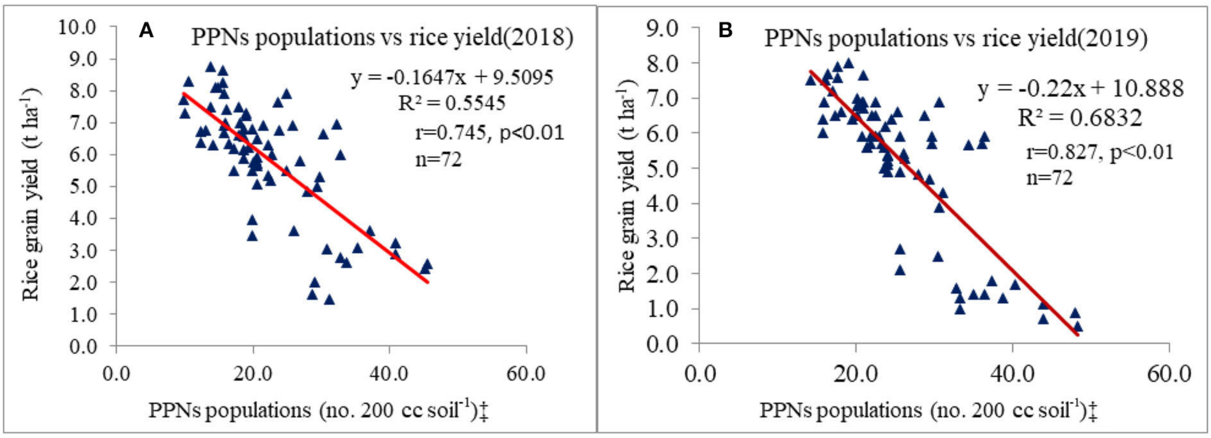

FIGURE 3
Relationship between plant parasitic nematodes (PPNs) populations and rice grain yield **(A)** during 2018 and **(B)** during 2019. ‡PPNs data were transformed through square-root $(x + 0.5)^{½}$ method before correlation analysis.

grassy, broad-leaved, and sedge weeds right from germination. Bispyribac controlled *E. colona, E. crusgalli* (grassy weeds); *E. alba*, *P. niruri*, *A. philoxeroides, T. portulacastrum* (broad-leaved weeds) effectively; and had little effect on *C. esculentus, C. rotundus*, *C. difformis*, and *C. iria* (sedges). It was not effective against newly emerged grassy weeds *D. aegyptium, D. retroflexa,* and *L. chinensis*. Cyhalofop applied in a sequence-controlled *E. colona*, *E. crusgalli*, *D. retroflexa*, *L. chinensis*, and *E. indica* effectively and *D. aegyptium* moderately. Thus, the sequential application of pyrazosulfuron *fb* cyhalofop *fb* bispyribac led to better weed control in DSR. The tank-mix of cyhalofop+bispyribac was inferior in controlling grassy weeds than their sequential application, probably, due to antagonism. Ottis et al. (2005) also reported antagonistic effects of cyhalofop with halosulfuron, triclopyr, and propanil in rice.

Nematodes dynamics and management

In this study, besides rice, five weeds (*E. colona, E. crusgalli, D. retroflexa, E. indica,* and *E. alba*) had RKN galls and were alternate hosts. These weeds are present in the global list of 24 weed hosts of RKN (Rich et al., 2009) except *D. retroflexa*, which might be a new host not reported earlier. Higher the weed density, the higher the population of RKN and total PPNs and *vice-versa*. The associations of these nematodes with weeds led to a reduction in rice yield. There was a direct relationship between RKN galls of these weeds and RKN galls in rice. Puddling and continuous submergence leading to the absence of some weeds or poor weed growth were responsible for the absence or negligible infestation of RKN, *T. brevilineatus,* and *P. thornei* in PTR (Table 9). In contrast, non-flooded aerobic soil conditions and intermittent irrigations were responsible for the higher infestation of PPNs under DSR (Jain et al., 2012; Kyndt et al., 2014). However, the triple ZT cropping system with residue (C5) led to reductions in RKN by 27, 15, 43, and 12% and *T. brevilineatus* by 66, 31, 38, and 60%, respectively, in soil compared to C1, C2, C3, and C4 (mean of 2 years) (Table 9). This CA practice also led to reducing RKN galls significantly in *E. colona, E. crusgalli,* and rice (Section 3.2). Rotation with non-host crop mungbean could be more useful to control RKN in this treatment. Besides, higher organic matter accumulation through rice, wheat, and mungbean residues and improved soil conditions led to the suppression of soil pathogens including PPNs (Kandel et al., 2017; Liu et al., 2019). Widmer et al. (2002) reported that adding organic matter through cover/rotational crop residue, green manure, compost, or organic amendment could influence PPNs and free-living nematodes. Rotating non-host crops such as mustard, sesame, and millet can also reduce RKN. *Sesbania* brown manuring was useful in maize (Das et al., 2020a), but *Sesbania* brown manuring (C3) invited more PPNs in DSR. *Sesbania* is a host of rice RKN and its decomposition releases some biocides in the rhizosphere stimulating nematodes might be the reason. The application of pyrazosulfuron *fb* cyhalofop *fb* bispyribac through better weed control led to 23, 66, 81, and 49% reduction in RKN, *T. brevilineatus, P. thornei*, and *H. oryzeae*, respectively, compared to UWC (mean of 2 years). Herbicides affect nematodes indirectly by altering the composition and density of weeds (Yeates et al., 1999), *albeit* sometimes they may have direct toxicity to nematodes. Das et al. (2010) reported the effect of atrazine and pendimethalin on PPNs. Herbicides causing mortality of weeds/host plants lead to non-availability of weeds/alternate host plants, which can bring down PPNs. Our results showed significant positive correlations between RKNs galls of weeds and rice (Figures 2A,B) and indicated the indirect

TABLE 10 Interaction between CA and weed control/herbicides treatments on grain yield of rice (t ha^{-1}) in 2018 and 2019.

CA practices (C)	Weed control treatments (W)									
	2018					2019				
	UWC (W1)	Pendi. *fb* bisp.(W2)	Pyraz. *fb* cyhal. + bisp.(W3)	Pyraz. *fb* cyhal. *fb* bisp.(W4)	Mean	UWC (W1)	Pendi. *fb* bisp.(W2)	Pyraz. *fb* cyhal. + bisp.(W3)	Pyraz. *fb* cyhal. *fb* bisp.(W4)	Mean
ZTDSR-ZTW(C1)	2.62	7.18	6.53	7.47	5.95	0.70	6.43	5.76	7.02	4.98
ZTDSR + WR – ZTW+RR(C2)	1.70	6.55	5.68	6.75	5.17	1.33	5.97	5.36	6.47	4.78
ZTDSR + WR+BM – ZTW+RR(C3)	2.80	6.05	5.55	6.35	5.19	1.50	5.51	5.14	6.30	4.61
ZTDSR-ZTW-ZTMB (C4)	3.30	5.93	5.25	6.43	5.23	1.37	5.63	5.07	6.27	4.59
ZTDSR + MR-ZTW + RR-ZTMB + WR(C5)	3.67	7.22	6.68	7.77	6.33	2.43	6.77	5.93	7.37	5.63
TPR-CTW(C6)	5.05	7.85	7.28	8.29	7.12	4.30	7.20	6.33	7.83	6.42
Mean	3.19	6.80	6.16	7.18		1.94	6.25	5.60	6.88	
			Tukey' HSD ($p \leq .05$)					Tukey' HSD ($p \leq .05$)		
CA practices (C)			0.68					0.53		
Weed control treatments (W)			0.28					0.31		
C x W			0.90					0.83		

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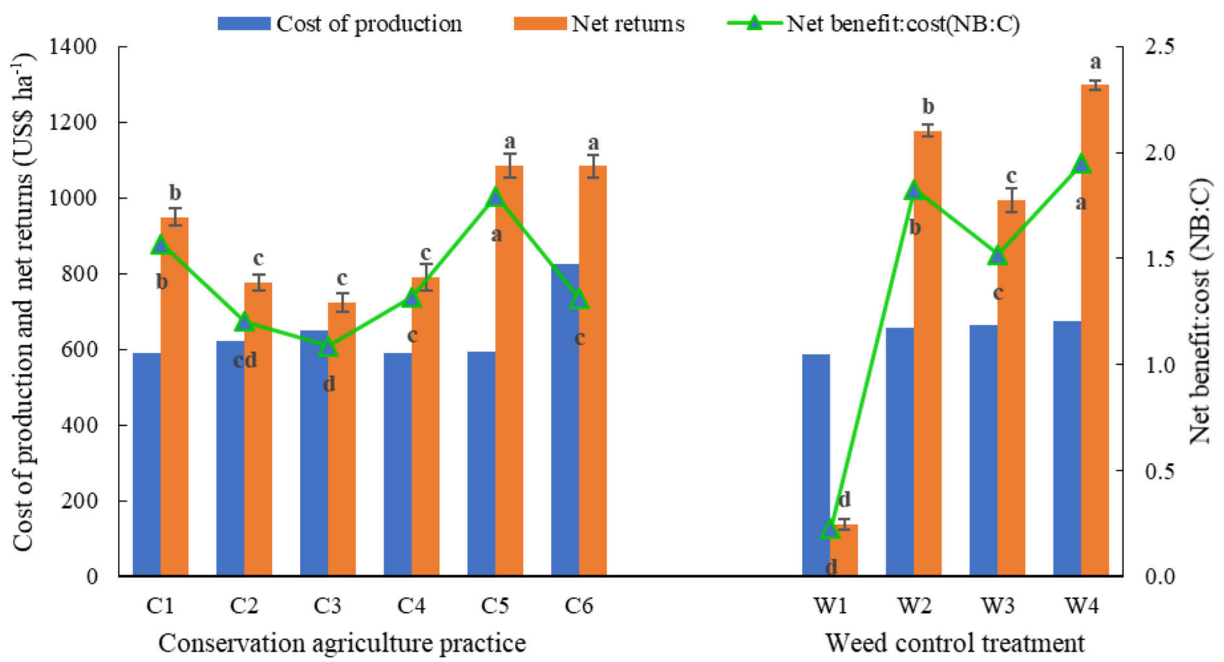

FIGURE 4
Benefit–cost economics of rice cultivation as influenced by CA and weed control practices (mean of two years). Mean having different lowercase letters on the vertical bars are significantly different at $p \leq 0.05$ as per Tukey's HSD test. Vertical bars represent mean ± standard error. C1–C6 and W1–W4 are treatments mentioned in Table 1.

effect of herbicides on RKNs. This conforms with Noling and Gilreath (2002) and Kutywayo and Been (2006).

Rice yield, economics, and herbicides residue

The variation over the years in rice yield was due to prevailing weather conditions, mainly rainfall, temperature, and sunshine (Supplementary Figures 1A,B). In 2018, higher rainfall (922.6 mm against 546.7 mm in 2019) from June to November (Supplementary Figure 1B), lower fluctuation in maximum and minimum temperatures (Supplementary Figure 1A) during the growth period, and greater availability of bright sunshine hours during the reproductive phase of rice led to better partitioning of photosynthates to grains and gave higher yield in both DSR and TPR. The DSRs, experiencing more biotic (weed and nematode) and abiotic (Fe deficiency and moisture) stresses had lower rice yield than PTR (Table 10). However, the triple ZTDSR with three crops residue (C5) gave a 9.4–22.0% higher yield than other ZTDSRs and was closer to PTR. This CA-based DSR, besides having better weed/nematode control, had better soil physical (aggregation, porosity, water content, soil strength) (Mondal et al., 2019) chemical (C and N accumulation) (Bhattacharyya et al., 2015) and biological (microbial biomass carbon, phosphatase, dehydrogenase, and β-glucosidase activities) conditions (Jat et al., 2020), which could help to achieve higher yield. Similarly, better weed control and consequently, a lower infestation of PPNs led to higher rice yield in the pyrazosulfuron *fb* cyhalofop *fb* bispyribac treatment. Relatively higher yield and lower cost of production made the triple ZT system with three crops residue (C5) superior to other DSRs (Figure 4), and comparable with PTR in terms of net returns, despite PTR having higher grain yield than C5. This amply highlighted that the CA-based DSR (C5) could be an equally remunerative alternative to PTR (Gathala et al., 2013; Baghel et al., 2020) and a more climate-resilient practice through a considerable reduction in methane emission (not reported here). The pyrazosulfuron *fb* cyhalofop *fb* bispyribac treatment required a slightly higher cost (Figure 4), mainly, due to the extra cost incurred on herbicides but a higher yield (176.1% higher than UWC) obtained in this treatment through better weed and nematode control led to higher net returns than other weed control treatments.

Our study indicates how weed control using herbicides indispensable for harnessing higher yield and income in DSR. Injudicious use of herbicides may have adverse effects on the environment and human health. We studied the herbicides at their recommended doses, which could hardly inflict any observable effect. For example, the residues of pendimethalin, pyrazosulfuron, bispyribac, and cyhalofop in rice grains and

TABLE 11 Herbicides residue (mg kg^{-1}) in soil (0–15 and 15–30 cm depths), and in rice grains and straw across the CA and weed control practices at harvest of rice crop.

Treatments	Residue in soil (mg kg^{-1})		Residue in rice grains and straw
	Pendimethalin (0–15 cm)*	Bispyribac, cyhalofop, and pyrazosulfuron (0–15 and 15–30 cm depths)	Bispyribac, cyhalofop, pendimethalin, and pyrazosulfuron
CA practices			
ZTDSR-ZTW (C1)	0.017	BDL	BDL
ZTDSR + WR –ZTW + RR (C2)	0.018	BDL	BDL
ZTDSR + WR+BM – ZTW+RR (C3)	0.014	BDL	BDL
ZTDSR-ZTW-ZTMB (C4)	0.018	BDL	BDL
ZTDSR+MR-ZTW+ RR-ZTMB +WR (C5)	0.018	BDL	BDL
PTR-CTW (C6)	0.013	BDL	BDL
Weed control treatments			
UWC (W1)	BDL	BDL	BDL
Pendi. *fb* bisp. (W2)	0.016	BDL	BDL
Pyraz. *fb* cyhal. + bisp.(W3)	BDL	BDL	BDL
Pyraz. *fb* cyhal. *fb* bisp.(W4)	BDL	BDL	BDL

*At 15–30 cm depth of soil, the residues of pendimethalin was below detectable level (BDL).

straw obtained from this study were below detectable levels, and rice grains and straw were safe for consumption by humans and animals, respectively. The FSSAI (2017) has already fixed the maximum residue limit (MRL) of pendimethalin, pyrazosulfuron, and bispyribac in rice grains as 0.05, 0.01, and 0.05 mg kg^{-1}, respectively. In soil, a negligible amount of pendimethalin was detected at harvest but was safe for rotational crops like wheat (data not shown). All four herbicides were applied within 25 DAS, and rice was harvested after 115–120 DAS. A long time (∼90–95 days) had elapsed, and herbicides were degraded in rice plants and soil through physical, chemical, and microbiological means, leading to below detectable levels of residues. Of course, a lower dose of application of these herbicides (<100 g ha^{-1}) except pendimethalin also played a role.

Conclusion

This study revealed that a CA-based triple ZT system, involving ZT direct-seeded rice (DSR) with mungbean residue - ZT wheat with rice residue - ZT mungbean with wheat residue combined with the application of pyrazosulfuron *fb* cyhalofop *fb* bispyribac could provide comparable rice yield through better weed and nematode control and would be an alternative to puddled transplanted rice (PTR). Among 14 weeds observed in rice, 5 (*Echinochloa colona, Echinochloa crusgalli, Dinebra retroflexa, Eleusine indica,* and *Eclipta alba*) were alternate hosts of root-knot nematodes (RKNs). Herbicides pyrazosulfuron *fb* cyhalofop *fb* bispyribac led to effective weed control in DSR. But, weed dynamics takes place over time in crop field ecosystem, and, therefore, dynamic herbicide recommendations through herbicide rotation may be resorted for better weed control in DSR in the future. Herbicide, crop residue, ZT, and non-host summer crops/mungbean would break the cycle of RKNs and reduce the infestations of RKNs and other plant parasitic nematodes (PPNs) in DSR. The direct effect of herbicides (pendimethalin, pyrazosulfuron, cyhalofop, or bispyribac) on these nematodes should be studied, which could not be studied in this study. Greater yield variability in ZTDSR should be addressed through focussed future research on developing newer varieties tolerant to various biotic (weeds, nematodes) and abiotic stresses (Fe and Zn deficiency and moisture shortage). This study would help to design integrated pest management modules involving interactions among weeds, nematodes, insect pests, and diseases, which might lead to a more productive and profitable CA-based DSR across diverse rice ecologies.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

RR: conceptualization, investigation, and writing-original draft preparation. TD: conceptualization, methodology, and writing–reviewing and editing. P: methodology. TB:

methodology and investigation. AG and RB: reviewing and editing. DC and SP: editing. SB: writing, review, and editing. VK and SS: original draft preparation. SG: methodology. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2022.1017013/full#supplementary-material

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Household decision-making, women's empowerment, and increasing egg consumption in children under five in rural Burkina Faso: Observations from a cluster randomized controlled trial

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Malnutrition is one of the most long-suffering problems facing women and children across the world—it is endemic to many low- and low-middle income countries and is a leading comorbidity in CU5 mortality. Malnutrition and food security are gendered issues; not only are boys and girls differently affected by these issues, but societal norms and differing roles of women and men are often drivers of these different outcomes. The United Nations seeks to address both malnutrition and gender inequality by reaching its Sustainable Development Goals by 2030. Researchers have shown that women's empowerment is inextricably linked to the nutritional outcomes of children. As one dimension of women's empowerment, intra-household decision-making is an important determinant of child health and nutrition outcomes, as it can determine how resources are allocated within the household. To better understand how gender inequalities within household decision-making may contribute to child nutrition, this study examines the association between household decision-making and the adoption of behavior change to increase chicken egg consumption among infants and young children in Burkina Faso, and explores the relationship(s) between the *Un Oeuf* project and women's empowerment. This study analyzes data collected during the *Un Oeuf* cRCT (July 2018–April 2019) and additional data that were collected in conjunction with the *Un Oeuf* endline household survey in April 2019. Significant relationships were found between women's household decision-making about eggs and child egg consumption at the end of the project. This was true for women who did not have decision-making power at baseline ($p = 0.006$, OR 3.822) as well as for women who indicted having had that power and sustaining it through endline ($p = 0.013$, OR 6.662). Results indicate that the *Un Oeuf* project significantly increased women's household decision-making ($p > 0.005$, OR 4.045). Finally, significant relationships were found between a woman's overall level of empowerment and household decision-making power surrounding (1) what is done with household eggs ($p < 0.005$, OR 2.87) and (2) how foods are portioned ($p = 0.012$, OR 6.712). These findings illustrate the importance and potential of women's decision-making as a point of entry to improving nutritional outcomes through changes in empowerment.

KEYWORDS

sustainable develop goals, nutrition, women's empowerment, household decision making, food security, children under five, animal source food, egg consumption

Introduction

Malnutrition is one of the most long-suffering problems facing children under 5 (CU5) across the world, endemic to many low- and low-middle income countries (LMIC), and a leading comorbidity in CU5 mortality (Müller and Krawinkel, 2005; Sundaram, 2012; Bain et al., 2013; UNICEF, 2019). The United Nations prioritizes this global issue with its explicit inclusion in the Sustainable Development Goals (SDGs) under SDG 2, or "Zero Hunger" (WCF(UK), 2017). Global aspirations and understandings of food security have evolved toward nutrition security, or the conditions under which "all people, at all times, have physical, social and economic access to food which is safe and consumed in sufficient quantity and quality to meet their dietary needs and food preferences, and is supported by an environment of adequate sanitation, health services and care, allowing for a healthy and active life" (Bhagowalia et al., 2010; Cunningham et al., 2015; Workicho et al., 2016; Galiè et al., 2019). This reframing positions nutrition security as the foundation upon which many other SDGs will be achieved, including good health and well-being, quality education, gender equality, decent work and economic growth, and reduced inequalities (WCF(UK), 2017). Importantly, researchers have shown that women's empowerment (WE) is inextricably linked to the nutritional outcomes of children. As one dimension of women's empowerment, intra-household decision-making is an important determinant of child health and nutrition outcomes, as it can determine how resources are allocated within the household (Peterman et al., 2021). In this paper, we explore the relationship between women's empowerment and household decision-making and the role of each in an intervention conducted in Burkina Faso to increase egg consumption in infants and young children.

Malnutrition and women's empowerment

Nutrition studies have shown that malnutrition can be mitigated and outcomes improved through a variety of intervention strategies, including education and empowerment of mothers through training programs on nutrition and safe animal husbandry practices (Olney et al., 2015; Haselow et al., 2016), as well as improved nutrient intake through the inclusion of ASF in the child's diet, including egg consumption (Iannotti et al., 2017; Omer et al., 2018). Animal source food (ASF) consumption can improve the growth, nutritional status, cognitive development, and overall health of a child when it is regularly included in the child's diet, especially during critical times of development (Neumann et al., 2003; Darapheak et al., 2013). Unfortunately, both egg and other ASF consumption are low in most LMIC, particularly among women and children. In these countries, women's educational status is also often low, with many women achieving less than primary or secondary school completion—both of which are associated with childhood malnutrition and low women's empowerment (Oxaal, 1997; Jin and Iannotti, 2014; Haggblade et al., 2016). Furthermore, in Burkina Faso as in other parts of Africa, cultural beliefs and stigma further limit ASF consumption, creating barriers that significantly constrain its consumption among population sub-groups such as pregnant women and young children, in particular the consumption of chicken eggs (Rogers, 1996; Iannotti and Lesorogol, 2014). There is growing evidence that targeting and empowering mothers in livestock production and programing may improve child nutrition outcomes through increased ASF consumption (Chen et al., 2021). Primary female caregivers (most often, but not always, mothers) can play an essential role in improving childhood nutrition; therefore, it is critical to involve and train them in livestock production. A more holistic approach that combines livestock and nutritional knowledge, attitudes, and practices is needed if the nutritional status of CU5 is to improve through the regular inclusion of ASF in their diets.

Women's empowerment and household decision-making

Women's empowerment is a complex and contested concept, for which different definitions exist, are variable across contexts, and are subjective in nature. While women's empowerment is difficult to measure holistically, several tools have been developed to both quantitatively and qualitatively capture and measure selected aspects of empowerment. In 2012, the International Food Policy Research Institute (IFPRI), in collaboration with Oxford Poverty and Human Development Initiative (OPHI) and USAID's Feed the Future, launched a new tool designed to measure women's empowerment within agricultural contexts—the Women's Empowerment in Agriculture Index (WEAI). This tool has since been modified in numerous forms, including an abbreviated version (A-WEAI). The latter measures five domains of women's empowerment (production, resources, income, leadership, and time) through six indicators (input in productive decisions, ownership of assets, access to and decisions on credit, control over use of income, group membership, and workload). The application of these domains of empowerment into research inquiries provides insight into the roles of women in the livestock sector (Malapit et al., 2017).

Women's agency has been associated with improved nutritional outcomes (Jones et al., 2019). Often measured by the degree of women's decision-making within the household, this dimension of empowerment can play an important role in determining the nutritional outcome of children (Doss, 2013). In order to understand the relationship between women's empowerment and ASF consumption, it is helpful to examine a woman's level of household decision-making specific to nutritional aspects of her family life that may either facilitate or constrain ASF consumption by her child(ren) (Agarwal, 1997; Ahmed, 2006; Seebens, 2011; Richards et al., 2013).

This study will examine both women's empowerment, as defined by the five domains of empowerment (5DE) within the A-WEAI, and household decision-making related to ASF consumptions as predictors of an improved nutritional behavior (child egg consumption). The decision-making questions were tailored to decisions surrounding nutrition and egg consumption, which was the targeted behavior of the *Un Oeuf* intervention. Overall empowerment was measured only at endline through the A-WEAI and thus measures a broader set of domains, reflective of Kabeer's and other scholars' conceptual frameworks, which went into the development of the WEAI tools.

Burkina Faso

Burkina Faso is a low-income country (LIC) which suffers from high rates of malnutrition, anemia, and stunting in CU5 (INSD, 2012). Much of this burden is attributable to high levels of food insecurity, inadequate complementary feeding practices, and poor dietary diversity, including insufficient levels of ASF consumption (Stewart et al., 2013). As with many other low-income countries, the rate of child mortality in Burkina Faso is closely associated with the nutritional status of the children (UNICEF, 2012). Childhood malnutrition can cause severe disease that impairs a child's physical and mental development and increases the overall chance of mortality from other illnesses.

Gender inequalities are pervasive in Burkina Faso, and strongly impact outcomes within maternal and child health (Nikièma et al., 2008; Isler et al., 2020). According to the Gender Gap Index (GGI) developed by the United Nations Development Programme, Burkina Faso ranks 182nd in the world with a Gender Inequality Index of 0.434—meaning that women's achievements in the measured domains are only 43% as those by men (UNDP, 2019). Gender inequalities are far reaching, extending into the political, educational, economic, health, nutrition, and intra-household domains. Women's under-achievements in several domains at once severely impact the nutritional and overall health outcomes in children, since women's empowerment has long been shown to directly impact both (Ayele and Peacock, 2003; Nelson and Stathers, 2009; Kariuki et al., 2013).

Un Oeuf study

Responding to a call for innovative, holistic approaches to combat malnutrition in CU5 in Burkina Faso (Request for Applications (RFA) No. RFA AID-OAA-L-15-00003-Livestock Systems Innovation Lab-03), researchers from the University of Florida and the *Institut de l'Environnement et Recheres Agricoles* (Environmental Institute for Agricultural Research; INERA) designed a cluster randomized controlled trial (cRCT; *Un Oeuf)* to test a culturally tailored behavior change intervention designed to increase infant egg consumption in the Kaya Department of rural Burkina Faso. The *Un Oeuf* study's intervention was conducted between July 2018 and April 2019. The intervention tested in the *Un Oeuf* cRCT aimed to increase egg consumption in infants 6–12 months old by increasing production and productivity of household livestock assets (chickens) and empowering mothers through educational trainings on agriculture and nutrition. The *Un Oeuf* study had three research arms consisting of (1) a full intervention group, in which enrolled children were gifted chickens at the onset of the project and enrolled mothers received monthly Integrated Nutrition and Agriculture (INA) trainings throughout the length of the project; (2) a partial intervention group, in which enrolled mothers received the same monthly INA trainings as the full intervention group (but no asset); (3) and a control group, in which mothers received neither trainings nor livestock assets.

The study was designed to explicitly engage women's empowerment in agriculture as a pathway to achieving its goal: child egg consumption. This was operationalized by targeting rural women with an infant 6–12 months of age with training (which aimed to improve knowledge, attitudes, and practices related to poultry production and human nutrition), targeting husband as well as community leaders for support of the project, establishing cohorts of mothers who provided social support to the activities of the program, equipping the mothers with educational materials of their own, both to reinforce knowledge and to become teachers to those around them, and providing one-on-one counseling and support to meeting the goals of the project. The study collected data at baseline and endline on four dimensions of household decision-making related to nutrition. Subsequently, at the end of the study, additional funding allowed for a follow-up study (the Enhance study) to examine women's empowerment, as indicated by the A-WEAI. This occurred at endline of the *Un Oeuf* study, in April 2019.

Study aims

Using household decision-making surrounding nutrition and women's empowerment at endline, as defined by the A-WEAI, this study aims to (1) examine the statistical associations between household decision-making surrounding nutrition and chicken egg consumption among IYC; (2) test the effect of the *Un Oeuf* project intervention on household decision-making surrounding nutrition; and (3) explore the overall relationship between household decision-making regarding nutrition and women's empowerment within the study population.

Methods

Study location and population

This study was conducted in the Kaya Department within the Sanmatenga Province of the Center-Nord Region of Burkina Faso. The study population for this study ($n = 260$) is identical to that of the *Un Oeuf* study, having enrolled those participants for the Enhance study. The full participant recruitment and enrollment protocol can be found elsewhere (Stark et al., 2021). Children were 6–12 months old at enrollment and were followed for 10 months. A total of 260 mother-child dyads were used for this study.

Study design

This longitudinal study leverages data collected during baseline and endline of the *Un Oeuf* cRCT (July 2018–April 2019), and uses additional data from the Enhance Study, which was collected in conjunction with, and simultaneous to, endline data collection of the *Un Oeuf* study (April 2019).

Data collection instruments

Household survey

For this study, a household was defined as a "shared cooking pot". The household survey (HHS) was successfully administered to and completed by 260 mother-child dyads at baseline of the *Un Oeuf* study. Basic demographics, including gender, age, age at first live-birth, marital status (including presence of co-wives), and education level of the respondent, were all controlled for within the cRCT study design.

The HHS sections relevant to this paper are those on household demographics; knowledge, attitudes, and practices of household child-feeding, with an emphasis on egg consumption; and household decision-making (HHDM) data. The HHS section on knowledge, attitudes, and practices of household child-feeding was tailored to assess the observable behavior change across research arms, as well as to understand current and past feeding practices with an emphasis on egg consumption. Questions were also included to understand who makes household decisions surrounding nutrition and division of food resources. The aim of these questions was to assess the level of decision-making the mother had within her household, any intervening change from baseline to endline, and what, if any, effect this change in decision-making had on egg consumption. Household decision-making surrounding nutrition included four variables—who decides, whether "self" or "other", (1) what foods are fed to children (HHDM-F), (2) what foods are bought (HHDM-B), (3) how foods are portioned (HHDM-P), and (4) what is done with household eggs (HHDM-E). The HHDM are thus binary variables and were collected at both baseline and endline.

Abbreviated women's empowerment in agriculture index

Quantitative women's empowerment data were collected at a household-level using the Abbreviated Women's Empowerment in Agriculture Index (A-WEAI). This tool uses a validated questionnaire designed to measure women's inclusion and agency in the agricultural sector. It was created to be administered to household-gender-pairs of men and women, to generate a score for women's (and men's) 5 Dimensions of Empowerment (5DE) and a gender parity index due to a lack of male participants. In this study, the questions were only administered to women, thus generating a women's empowerment score based on the 5DE, without consideration of gender parity. Adequacy scores are first determined for each indicator of empowerment and a respondent is considered to be empowered if she is adequate in at least 80% of the indicators. The A-WEAI questionnaire was used to gather 5DE data at endline, within the same 260 households that also took part in the HHS at baseline and endline. An electronic version of A-WEAI questionnaire, implemented in RedCap as originally developed (Malapit et al., 2017), was used to gather 5DE data within the same 260 households that also took part in the HHS at baseline and endline.

Data collection

Quantitative data were collected from all available mother-child dyads enrolled in the *Un Oeuf* study at baseline and endline. Women were surveyed using a questionnaire, which consisted of the *Un Oeuf* study HHS and the A-WEAI (only at endline). The HHS gathered basic household demographic information; livestock knowledge, attitudes, and practices; household nutrition; household decision-making; water and sanitation; egg consumption of the enrolled child; and other information (see Stark et al., 2021). The A-WEAI questionnaire was used to generate the 5DE, after having been tailored by local members of the study team for cultural relevancy, with assistance of highly experienced in-country gender experts.

Data were collected using a team of graduate students from the University of Ouagadougou, Burkina Faso. University of Florida researchers trained data collectors for the *Un Oeuf* HHS prior to the start of the project. Additional training on implementation of the A-WEAI was provided by the local gender experts during the Spring of 2019, prior to endline data collection. The team pilot tested 5DE data collection and made necessary modifications for the local context.

Data management, quality control, and preparation

Data management for data collected in both the *Un Oeuf* and Enhance studies was conducted in REDCap, while data organization, standardization, and cleaning procedures were carried out using Microsoft Excel and R Studio. Quality control procedures were conducted with all longitudinal data, and mother-child dyads were verified by participant and household IDs against enrollment information for each month of data collection.

The 5DE data were prepared and analyzed in using standard protocol as developed (Malapit et al., 2017), implemented in R with IFPRI validated scripts using the electronic data downloads from the RedCap. Indicators for each domain of empowerment were generated for each respondent then an overall 5DE score was generated using the weighted average score as explained in the standard protocol (Malapit et al., 2017). These indicators were used in linear regression models to examine the relationship between each subdomain of empowerment and behavior change (egg consumption) as captured by household surveys.

Data analysis

The variables used in this study include: four variables on household decision-making regarding nutrition, the overall 5DE adequacy score and associated sub-domains of empowerment, and child egg consumption. The primary variables were derived

TABLE 1 Baseline summary statistics for the study population.

		Baseline summary statistics			
		Control ($n = 88$)	**Partial ($n = 89$)**	**Full ($n = 83$)**	**Total ($n = 260$)**
Egg consumption	No	76 (86%)	82 (92%)	76 (92%)	234 (90%)
	Yes	12 (14%)	7 (8%)	7 (8%)	26 (10%)
HHDM-F	Other	22 (25%)	29 (33%)	33 (40%)	84 (32%)
	Self	62 (70%)	58 (65%)	49 (59%)	169 (65%)
	No response	4 (5%)	2 (2%)	1 (1%)	7 (3%)
HHDM-B	Other	77 (87%)	82 (92%)	76 (92%)	235 (90%)
	Self	7 (8%)	5 (6%)	6 (7%)	18 (7%)
	No response	4 (5%)	2 (2%)	1 (1%)	7 (3%)
HHDM-P	Other	39 (15%)	38 (43%)	46 (55%)	123 (47%)
	Self	45 (80%)	49 (55%)	36 (44%)	130 (50%)
	No response	4 (5%)	2 (2%)	1 (1%)	7 (3%)
HHDM-E	Other	57 (65%)	54 (61%)	58 (70%)	169 (65%)
	Self	26 (29%)	33 (37%)	24 (29%)	83 (32%)
	No response	5 (6%)	2 (2%)	1 (1%)	8 (3%)

These data were collected in July 2018.

TABLE 2 Endline summary statistics for the study population.

Endline summary statistics		Control ($n = 88$)	Partial ($n = 89$)	Full ($n = 83$)	Total ($n = 260$)
Egg consumption	No	33 (38%)	1 (1%)	0	34 (13%)
	Yes	54 (61%)	85 (95%)	79 (95%)	218 (83.9%)
	Not surveyed	1 (1%)	3 (4%)	4 (5%)	8 (3.1%)
HHDM-F	Other	0	2 (2%)	0	2 (0.8%)
	Self	87 (99%)	83 (93%)	79 (95%)	249 (95.7%)
	No response	–	1 (1%)	–	1 (0.4%)
	Not surveyed	1 (1%)	3 (4%)	4 (5%)	8 (3.1%)
HHDM-B	Other	85 (97%)	84 (94%)	76 (92%)	245 (94.2%)
	Self	2 (2%)	1 (1%)	3 (3%)	6 (2.3%)
	No response	–	1 (1%)	–	1 (0.4%)
	Not surveyed	1 (1%)	3 (4%)	4 (5%)	8 (3.1%)
HHDM-P	Other	7 (8%)	11 (13%)	7 (8%)	25 (9%)
	Self	80 (91%)	74 (83%)	72 (87%)	226 (87%)
	No response	–	1 (1%)	–	1 (0.4%)
	Not surveyed	1 (1%)	3 (3%)	4 (5%)	8 (3%)
HHDM-E	Other	61	44 (49%)	29 (35%)	134 (51.6%)
	Self	26	41 (46%)	50 (60%)	117 (45%)
	No response	–	1 (1%)	–	1 (0.4%)
	Not surveyed	1 (1%)	3 (4%)	4 (5%)	8 (3%)
5DE overall score adequacy	Inadequate	50	53	39 (47%)	142 (55%)
	Adequate	33	33	40 (48%)	106 (41%)
	No response	3 (4%)	–	–	3 (1%)
	Not surveyed	2 (2%)	3	4 (5%)	9 (4%)

These data were collected in April 2019.

from both the household survey and the A-WEAI. Data were analyzed for study population baseline and endline summary statistics, which can be seen, respectively, in Tables 1, 2, stratified by research arm and total population.

HHDM and egg consumption at endline

Bivariate analyses were conducted using the binary dependent variable (egg consumption) against each of the four independent variables of household decision-making (HHDM-F, HHDM-B, HHDM-P, and HHDM-E measured at endline) to test for independence at a study-population level and significance into the model. A standard p-value of $\leq$0.20 was used as the threshold for inclusion into a binomial logistic regression model.[1]

1 Adjustment for a cluster effect within the models was deemed unnecessary following insignificant fisher's exact tests between all outcome variables of interest and clusters. The standard threshold value of 0.5 was used for predictability within all logistic regression models.

A binomial logistic regression model was conducted with the confidence interval set to 95% and a corresponding p-value of significance of $\leq$0.05, to determine the effects of household decision-making centered around egg consumption on the likelihood that participants would feed their child eggs.

Change in HHDM (ΔHHDM) and egg consumption at endline

Bivariate analyses were conducted using the dependent variable (child egg consumption in the past seven days) against each of the four categories representing change and directionality of change in household decision-making surrounding nutrition to test for independence and significance for inclusion into the regression model (p-value of $\leq$0.20). Statistically significant variables were then included in a logistic regression model, where a standard p-value of $\leq$0.05 was used to represent significance. The only HHDM variable to show significance below $p = 0.2$ for inclusion into the model was the variable for deciding what is done with the household's chicken

TABLE 3 Variables depicting the change in household decision-making from baseline to endline.

Categories of change in household decision-making			
ΔHHDM	**Baseline HHDM**	®	**Endline HHDM**
Positive change	Other	®	Self
Positive sustainment	Self	®	Self
Negative sustainment	Other	®	Other
Negative change	Self	®	Other

eggs. This variable is a four-category variable that examines the ΔHHDM from baseline to endline (Table 3).

A binomial logistic regression was performed to examine the effects a change in household decision-making centered around egg consumption (ΔHHDM-E) had on the likelihood that participants would feed their child chicken eggs.

Household decision-making and 5DE at endline

The four bivariate variables for household decisions-making (HHDM-F, HHDM-B, HHDM-P, and HHDM-E) at the endline timepoint. A chi-squared test for association was carried out against each of the four, endline HHDM variables (HHDM-F, HHDM-B, HHDM-P, and HHDM-E) against the bivariate 5DE score for inclusion into a logistic regression model. A logistic regression model was built using variables found to be significant at the $p \leq 0.2$ value using 95% confidence intervals and listwise deletion. Variables were considered to have a significant relationship if the coefficient results showed a final p-value of $\leq$0.05.

Relationship between Un Oeuf intervention and household decision-making

In this analysis, the three research arms of the *Un Oeuf* study (Control, Partial, and Full) represent the *Un Oeuf* intervention. A logistic regression was conducted to examine the relationship between the research arms of the *Un Oeuf* study and household decision-making to better understand if any individual relationship existed between the *Un Oeuf* intervention and either of the household decision-making areas shown to have a significant positive correlation with the 5DE score at endline—decision-making on what is done with the household eggs (HHDM-E) and on how food is portioned (HHDM-P). All models were built using 95% confidence intervals and listwise deletion. Statistical significance was determined to exist for any variable included into the regression model with a p-value ≤ 0.05.

All study participants received information that adequately allowed each participant to make a well-informed decision about whether to consent to participate in this study. All members of the in-country research team were fluent in the local language of Moré and French. Project documents were translated from English into French and copies were provided to the University of Florida Institutional Review Board (IRB) and the Burkina Faso Ethical Review Board (ERB). Both the UF IRB and the Burkina Faso ERB approved the study prior to the collection of any data.

Results

Household decision-making and egg consumption at endline

The results of the binomial logistic regression can be found in Table 4. Only one HHDM variable was found significant for entry into the model—endline decision-making on who decides what to do with the household eggs (HHDM-E). To control for baseline HHDM-E, the baseline HHDM-E metric was entered into the model as a covariate, which was not found to be significant within the model.

The model is found to be statistically significant, $\chi^2(2) = 15.50$, $p < 0.0005$. It explained 11.4% (Nagelkerke R^2) of the variance in egg consumption and classified 86.8% of all cases correctly. A non-significant Hosmer and Lemeshow Test ($p = 0.854$) showed that the data fit the model well. The model sensitivity was 100% with a positive predictive value was 86.83%. The covariate of HHDM-E at baseline was not found to be statistically significant; however, it did show that women who reported "self" decision-making at baseline were 1.969 times more likely to feed their child eggs at endline. The relationship between HHDM-E at endline and egg consumption was found to be statistically significant ($p = 0.002$). Women who reported "self" decision-making over what is done with the household eggs had 4.439 times higher odds of feeding their child chicken eggs than women who reported that someone else makes that decision.

ΔHHDM and egg consumption at endline

To examine the relationship between an observed change in household decision-making about egg consumption between baseline and endline and women feeding their child chicken eggs at endline, a binomial logistic regression was performed, where the dependent variable is a four-category variable that examines the change in HHDM-E from baseline to endline

TABLE 4 Logistic regression results for egg consumption based on HHDM-E at endline.

Logistic regression predicting likelihood of egg consumption based on HHDM-E at endline								
Predictor	***B***	**SE**	**Wald**	***df***	***p***	**Odds ratio**	**95% CI for**	
							Lower	**Upper**
HHDM-E at baseline	0.678	0.486	1.945	1	0.163	1.969	0.760	5.102
HHDM-E at endline	1.490	0.476	9.809	1	0.002*	4.439	1.747	11.281
Constant	2.286	0.273	70.192	1	0.000*	9.834		

*Denotes significant p-value; HHDM-E is for self compared to other.

TABLE 5 Logistic regression results for egg consumption based on change in HHDM-E from baseline to endline.

Logistic regression predicting likelihood of egg consumption based on change in HHDM-E from baseline to endline								
Predictor	***B***	**SE**	**Wald**	***df***	***p***	**Odds ratio**	**95% CI for**	
							Lower	**Upper**
Change in HHDM-E (negative sustainment)			12.263	3	0.007			
Change in HHDM about household egg decisions (negative change)	0.843	0.586	2.074	1	0.150	2.324	0.738	7.322
Change in HHDM about household egg decisions (positive change)	1.341	0.490	7.498	1	0.006*	3.822	1.464	9.977
Change in HHDM about household egg decisions (positive sustainment)	1.896	0.763	6.171	1	0.013*	6.662	1.492	29.745
Constant	2.192	0.256	73.457	1	0.000	8.951		

*Denotes significant p-value; change in HHDM-E is for negative sustainment compared to negative change, positive change, and positive sustainment.

(previously shown in Table 3). As with the previous model, HHDM-E was the only variable to show significance below $p = 0.2$ when running univariate correlations, and to be included in the regression. The logistic regression model was statistically significant, $\chi^2(3) = 14.027$, $p < 0.0005$. The model explained 9.9% (Nagelkerke R^2) of the variance in egg consumption and classified 86.5% of all cases correctly, and the Hosmer and Lemeshow goodness-of-fit test showed the model was a good fit ($p = 1.0$). The model sensitivity was 100% with a positive predictive value was 86.51%. The categories of HHDM of "positive change" and "positive sustainment" were found to have a statistically significant positive correlation with egg consumption at endline ($p = 0.006$ and $p = 0.013$, respectively). Women who reported a "positive change"—reported that at endline they make the decision about what is done with the household eggs whereas at baseline it was someone else making that decision—had 3.822 times higher odds of feeding their child chicken eggs than women who reported both at baseline and at endline that someone other than themselves makes that decision. Furthermore, women who reported making these decisions at baseline and sustaining that decision-making power at endline had 6.662 times higher odds of feeding their child chicken eggs than women who reported at both baseline and endline that someone else made that decision. See Table 5 for results.

HHDM and an 5DE score at endline

A chi-squared test for association was conducted between each of the four HHDM variables at endline and the adequacy score of the 5DE. Of the four HHDM variables centered around feeding practices, two were found to have a statistically significant ($p \leq 0.2$) positive association with the 5DE score—(1) who makes decisions about how foods are portioned and (2) who makes decisions about what to do with the household eggs. Subsequently, a logistic regression was performed to examine the relationship amongst HHDM-E (and HHDM-P) and 5DE score.

TABLE 6 Logistic regression results for empowerment adequacy based on HHDM-P and HHDM-E at endline.

Logistic regression predicting empowerment adequacy based on HHDM-P and HHDM-E at endline								
Predictor	***B***	**SE**	**Wald**	***df***	***p***	**Odds ratio**	**95% CI for**	
							Lower	**Upper**
HHDM-P at endline	1.904	0.762	6.247	1	0.012*	6.712	1.508	29.871
HHDM-E at endline	1.056	0.275	14.773	1	0.000*	2.876	1.678	4.929
Constant	−1.109	0.380	8.509	1	0.004	0.330		

*Denotes significant p-value; HHDM-P and HHDM-E are for "self" compared to "other".

TABLE 7 Logistic regression results for egg consumption based on HHDM-E at endline.

Logistic regression predicting likelihood of egg consumption based on HHDM-E at endline								
Predictor	***B***	**SE**	**Wald**	***df***	***p***	**Odds ratio**	**95% CI for**	
							Lower	**Upper**
HHDM-E at baseline	0.836	0.480	3.039	1	0.081	2.308	0.901	5.911
Empowerment 5DE at endline	0.276	0.399	0.480	1	0.489	1.318	0.603	2.878
Constant	2.128	0.245	75.347	1	0.000	8.397		

HHDM-E at baseline is for "self" compared to "other", and empowerment is for "adequate" compared to "inadequate".

The logistic regression model was statistically significant, $\chi^2(2) = 30.787$, $p < 0.0005$. The model explained between 11.7% (Cox and Snell R^2) and 15.7% (Nagelkerke R^2) of the variance 5DE adequacy and classified 66% of all cases correctly, while Hosmer and Lemeshow test was not significant ($p = 0.882$) and showed the model to be a good fit. The model sensitivity was 64.2%, specificity was 67.4%, positive predictive value was 59.65%, and a negative predictive value was 71.43%. Both HHDM-E and HHMD-P were significant within the model ($p < 0.0005$ and $p = 0.012$, respectively), and showed that an increase in either resulted in an increase in likelihood for an adequate 5DE score. Women who reported making decisions about what is done with the household eggs were 2.876 times more likely to have an adequate 5DE score compared to women who reported others making those decisions. Similarly, women who reported making decisions about how food is portioned were 6.712 times more likely to have an adequate 5DE score compared to women who reported not making those decisions. See Table 6 for results.

Women's empowerment (5DE) and egg consumption at endline

A chi-squared test for association was performed to examine if any significant association existed between 5DE score and egg consumption at endline. The test showed no significant relationship between the two variables. To further confirm these results, a logistic regression was performed with egg consumption as the dependent variable and 5DE as a regressor—HHDM-E was controlled for at baseline—the model was not significant ($p = 0.489$) (Table 7).

Relationship between *Un Oeuf* study and women's empowerment

Since a significant statistical relationship was shown to exist between, on the one hand, 5DE adequacy score and, on the other hand, HHDM-E and HHDM-P, logistic regressions were performed to explore the relationship between likelihood of egg consumption and HHDM-E and HHDM-P within each of the three research arms (full, partial, and control) of the *Un Oeuf* study.

No statistically significant relationship was observed amongst any of the three research arms and HHDM-P ($p = 0.531$). However, the logistic regression performed to examine the relationship between egg consumption amongst the research arms and HHDM-E was found to be statistically significant, $\chi^2(2) = 19.091$, $p < 0.0005$. The Hosmer and Lemeshow Test ($p = 0.997$) confirmed the data to be a good fit for the model. The model explained between 7.3 (Cox and Snell R^2) and 9.8% (Nagelkerke R^2) of the variance 5DE adequacy and

TABLE 8 Logistic regression results for egg consumption at endline based on HHDM-E across research arms.

Logistic regression predicting likelihood of egg consumption at endline based on HHDM-E across research arms

Predictor	*B*	SE	Wald	*df*	*p*	Odds ratio	95% CI for	
							Lower	Upper
Research arm (control)			17.950	2	0.000			
Research arm (partial)	0.782	0.319	5.999	1	0.014*	2.186	1.169	4.088
Research arm (full)	1.398	0.331	17.862	1	0.000*	4.045	2.116	7.734
Constant	−0.126	0.132	0.916	1	0.338	0.881		

*Denotes significant p-value; Research arm is for control compared to partial and full.

classified 61.8% of all cases correctly with a good model fit (Hosmer and Lemeshow, $p = 1.0$). The model sensitivity was 42.7%, specificity was 78.4%, positive predictive value was 63.29%, and a negative predictive value was 61.05%. The egg consumption in both the Full and Partial Research Arms were significant within the model with respective values of $p < 0.0005$ and $p = 0.014$ and showed that an increase was correlated with an increase in likelihood that a woman, herself, makes decisions on household eggs. Results (Table 8) showed that women in the partial intervention arm were 2.186 times more likely to report decision-making over what is done with eggs within the household compared to women in the control arm. Comparatively, women in the full intervention arm were 4.045 times more likely to report decision-making over what is done with eggs within the household compared to women in the control arm.

Discussion

Findings of these analyses contribute to the growing body of literature surrounding women's empowerment and animal source food consumption, underscoring that increasing a women's household decision-making ability surrounding the nutrition of her children is an important and direct pathway to increasing the ASF consumption of CU5 (Ayele and Peacock, 2003; Tolhurst et al., 2008; Lépine and Strobl, 2013; Richards et al., 2013; Jin and Iannotti, 2014). While no significant relationships were shown to exist between egg consumption and 5DE adequacy score, significant positive relationships were shown to exist at endline between women's household decision-making regarding nutrition (notably, HHDM-E and HHDM-P) and both egg consumption of CU5 and 5DE adequacy score. This finding highlights the importance of decision-making *about nutrition related resources and decisions,* something for which the A-WEAI does not directly account.

Intrahousehold bargaining power is extremely important to inspect within the concept of women's empowerment but can be difficult to understand if a study does not include information on the woman's role in household decision-making. Intrahousehold bargaining power can be thought of as the weight one can exert on the scales of decision-making within the household—some women have full control of specific domains with the support of their spouses, while others may have little to no control and are unable to tip the scale in their favor (Agarwal, 1997; Ahmed, 2006; Seebens, 2011). Literature shows that many projects have examined women's empowerment and childhood nutrition through household surveys and anthropometrics; however, a validated means for assessing women's empowerment is often missing from these study designs (Bhagowalia et al., 2010; Doss, 2013).

Regarding the impact of the *Un Oeuf* study on women's empowerment, it is apparent that the intervention successfully changed household decision-making in choices that significantly impact the consumption of ASF (eggs) in CU5. This can be seen in the relationship established between those who experienced a positive change in their own decision-making and egg consumption—a woman who was not previously making decisions about eggs who reports making those decisions by the end of the project was 3.82 times more likely to feed her child eggs compared to a woman whose decision-making power did not increase. This is important, because although other studies have shown a relationship between increasing broader dimensions of women's empowerment (as measured by A-WEAI and reflected in women's adequate 5DE score in this study) and increasing ASF consumption in children, this is not the only approach to increasing ASF consumption in children. A more direct pathway may be possible by focusing on *empowering women* to make decisions surrounding children's nutrition and consumption of specific forms of food, such as ASF. Our research indicates that it may be possible to change the balance of decision-making within the household in a manner that is favorable to support behavior change that increases ASF consumption in children prior to her being more generally "empowered", as indicated by tools such as the 5DE, which may take longer and may not be successful. Limitations to this study include the lack of women's empowerment data at baseline, which limited the ability to fully examine whether a change in overall women's empowerment (as measured by the 5DE) occurred within the study population and to what extent it was specific to the intervention, as well as the lack of men's participation in the A-WEAI. A possible limitation to this study is that survey respondents to questions about decision-making (outside of the A-WEAI) were asked who takes the decision, and options did not include joint decision-making. While this limits our ability to know where women made progress, provided input, or increased engagement with decision-making but did not report as "taking" the decision, this yielded results that are a conservative measure of where increased decision-making may have occurred. Consequently, women's engagement in decision-making, be that in bargaining power, influence, or joint decision-making, may be greater than that captured in our indicator. One strength this study had was the partnership with gender experts in Burkina Faso. This collaboration allowed for rigorous training of data collectors to facilitate high quality data collection of the A-WEAI. Additional strengths include a high degree of trust and rapport with the women in the study population, which aided in the response rate of all questions.

Conclusion

In conclusion, this study found a significant and positive relationship between women's decision-making and egg consumption among CU5. Importantly, overall women's empowerment (as indicated by the 5DE in this study) was not associated with CU5 egg consumption. Given the emphasis on women's empowerment as a pathway by which agriculture can improve nutrition, the study underscores the need to better understand which domains of empowerment are those that most directly affect nutritional outcomes; specifically, the potential for women's decision-making about household-produced ASF to directly affect own-consumption needs further study.

Data availability statement

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found below: https://dataverse.harvard.edu/dataverse/livestock-lab-burkina-egg-consumption.

Ethics statement

The studies involving human participants were reviewed and approved by University of Florida Institutional Review Board Committee of Ethics of the Government of Burkina Faso. Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin.

Author contributions

EM is the primary author who wrote this article with support and guidance from RS and SM. NS provided statistical expertise and coding for the scoring of the 5DE instrument and adherence to methodology. SM supervised the research and findings of this work as the principal investigator of the Un Oeuf study. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Getting ahead of the pandemic curve: A systematic review of critical determining factors for innovation adoption in ensuring food security

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The imminent threat to food security requires immediate intervention toward ensuring societal sustainability especially in combating the pandemic. The rapid spread of COVID-19 cases has caused concern for food security. A recent outlook report produced by Food Agricultural Organization and World Food Programme (FAO-WTP) highlights that there are at least 20 countries that are faced with a looming threat of food availability between the period of March-July 2021. Other factors that pose a significant threat to food security include climate change and natural disasters which could significantly reduce the yield. It is hence imperative to gain an in-depth understanding of factors that influence farmers' choices in innovation adoption for increased yield. A line of research has been conducted across the globe on new technology adoption and effect of innovation that aims to increase productivity and yield. This study examined the key factors, that lead farmers to the adoption of new technology and innovation, reported in studies over the past 15 years. PRISMA-P (Preferred Reporting Items for Systematic Review and Meta-Analysis Protocols) was employed based on the SCOPUS and Web of Science database. In creating the main dataset, a protocol was developed in advance to document the analysis method. Several inclusion (eligibility) and exclusion criteria were set to select related articles from a total of 2,136 papers. The thematic and content analyses were subsequently performed on 392 research articles. The findings indicate 4 over-arching segments, and 12 major determinants, that comprise 62 associate determinants. The paper concludes with the identification of critical factors for innovation adoption amongst farmers.

KEYWORDS

food crop, innovation, adoption, Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA), food security, diffusion, farmers

Introduction

The imminent threat to food security requires immediate intervention toward ensuring societal sustainability. A recent outlook report produced by Food Agricultural Organization and World Food Programme (FAO-WTP) highlights that there are at least 20 countries that are faced with a looming threat of food availability between the period of March–July 2021 (1). FAO further reported that 45 countries are in need of external assistance for food mostly due to the COVID-19 pandemic, which has severely aggravated global food security conditions (2). Despite the arguments that global calorie intake has shifted toward a more diversified diet that includes higher shares of meat, dairy products, fats, sugar, fruit and vegetables (3), staple food crops are still in demand. It is also reported that 50% of daily calorie intake is derived directly from cereal grain and staple food crops consumption (4).

Cereal grain and staple food crops are not only essential for human physiological demand, but they also act as a core economic driver for both society and a country. It is estimated that the annual global trade for cereal grain is pegged at 441 million tonnes (2), approximately 200 billion USD in terms of the crop trade value alone (see **Table 1** for the details). There is however, a serious threat of scarcity in staple food supply across many countries that are caused by numerous factors including climate change-related issues instance as water scarcity and natural disaster (5); COVID-19 pandemic (6); and rapid urbanization (7).

The gap between staple crop production and the demand for human food consumption has widened over the decades (3). There is hence a dire need to increase production that could be made possible through innovations. Green Revolution was previously implemented by several countries such as China, India, Malaysia, and other developing countries in the 1960s and 1970s. In the recent development of innovation in staple food crop farming, attention has expanded to include areas such as green technology, sustainable farming, and conservative agriculture.

There has been a line of studies on the diffusion of innovation and adoption of new technology amongst farmers. For instance, Nordin and colleagues identified that agriculture education is a significant determinant for farmers' agriculture adoption (8). They also found that social media affordances help farmers to reduce complexity in adopting new innovations (9). There are also several other studies that test various perspectives in explaining farmers' adoption of new innovations including adopting theories of planned behavior (10), identifying factors other than utility theories (11), government support as determining factors (12) and the usage of intention modeling (13). However, efforts to systematically review these studies are still lacking.

Most of the current systematic reviews found focus on the adaptation of efforts related to climate-resilient crops (14), climate change adaptation (5), climate change policy (15), non-agriculture community (16), and focused on other regions (17). This paper seeks to fill the gap in understanding and identifying the characteristics of innovation as well as the determinants of adopting them among staple food crop farmers. Studies, articles, and reports on adoption and diffusion of innovation in the peer-reviewed literature within the database are used in this study.

The review was guided by the main question of what determinants affect staple food crops farmers around the world to adapt to new technology and innovation in lieu of the recent pandemic crisis? The review primarily focuses factors affecting on farmers' adoption. Focusing on this aspect is pivotal as the world is currently expected to face several other crises including energy and economic crisis. By understanding this matter, it will help policymakers, innovators and stakeholders develop better strategic approaches to increase farmers adoption to innovation.

Methodology

The method used in this study referred to as PRISMA (18). The review is conducted on peer-reviewed articles found in two of the largest academic databases – SCOPUS and Web of Science (WOS). The approaches to conduct systematic review include identifying eligible and exclusion criteria, steps of the review process (identification, screening, eligibility) and data abstraction analysis.

Preferred Reporting Items for Systematic Reviews and Meta-Analyses

Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) was used as a guide for the review due to its three unique advantages. First, it enables the study to define clear research questions that permit systematic research. The PRISMA method has been used extensively for systematic review studies in social science (18–22). Second, the guidelines enable the identification of inclusion and exclusion criteria. Finally, it supports examining a large database in the scientific literature in a defined time. The PRISMA statement allows for a rigorous search of the term related to staple food crops farmers' adoption to innovation.

Resources

The systematic review was based on two main academic databases – SCOPUS and Web of Science (WOS). Both of the databases consist of more than 33,000 journals across 256 disciplines which include disciplines and subjects related to agronomy, multi-disciplinary agriculture, interdisciplinary

TABLE 1 Basic facts of world cereal grain.

Million tonnes	2018/19	2019/20 estimate	2020/21 forecast	Change: 2020/21 over 2019/20 (%)
Production	2,645.9	2,706.3	2,764.9	2.2
Developing countries	1,614.0	1,648.8	1,678.6	1.8
Developed countries	1,032.0	1,057.5	1,086.3	2.7
Trade	410.4	434.3	441.4	1.6
Developing countries	144.3	163.5	160.6	-1.8
Developed countries	266.1	270.8	280.8	3.7
Utilization	2,674.9	2,683.3	2,746.4	2.4
Developing countries	1,814.0	1,827.8	1,874.3	2.5
Developed countries	860.9	855.5	872.2	1.9
Per capita cereal food use (kg per year)	149.6	149.7	150.1	0.3
Stocks	868.1	880.9	895.5	1.7
Developing countries	677	691.5	696.7	0.8
Developed countries	191.2	189.4	198.8	4.9
World stock-to-use ratio (%)	32.4	32.1	31.8	-0.8

Data obtained from Food Agriculture Organization (2) Report – "Crop Prospects and Food Situation: Quarterly Report".

social sciences, food technology, social issues as well as development and planning. It includes comprehensive research data and citations, established by Clarivate Analytics and ranks them by three separate measures: citations, papers, and citation per paper. The second database is SCOPUS, a database product owned by Elsevier. It has more than 22,800 journals from around 5,000 publishers worldwide (23). Similar to WOS, the SCOPUS index consists of diverse subject areas which is suitable for this systematic review.

Search protocol – Eligibility and exclusion criteria

To create the main dataset, a protocol was developed in advance to document the analysis method. Several inclusion (eligibility) and exclusion criteria were determined. The first criteria are the literature type, only journal articles with primary data are selected. This means review articles, panel series data, book series, books, and conference proceedings are all excluded. The selection of only journal articles is to ensure only recent findings associated with innovation adoption can be captured in this systematic review. Furthermore, journal articles that are indexed by both databases have been through a rigorous peer review process. This shall ensure the methods used in their study have been validated and thus provide more concrete findings in this systematic review.

Second, to avoid any confusion and loss of meaning in translation, the protocols exclude non-English publication. Thirdly, concerning the timeline, which is sensitive to innovation, a period of 15 years was selected (between 2006 and 2021). This allows recent issues related to innovation adoption to be identified. The next criteria for the search protocol are the areas of research, only research related to staple food crops is selected. Staple food crops in this study include cereal grains (e.g., paddy, wheat, barley, maize, millet, and sorghum) as well as some tuber roots (e.g., yam, potato, and cassava) and plantain. Legumes, beans, and non-food crops are excluded. Finally, the search protocols only focus on adaption by farmers. **Table 2** summarizes the inclusion and exclusion criteria.

Systemic review process

Based on the guideline in PRISMA, four stages were involved in the systematic review process. The search was performed on 2 March 2021. The first phase identified the keywords used in the search process. Based on terminologies used in the past studies, keywords similar and related to innovation adoption, staple food crops and farming community were used. The search string used for the systematic review process is included as supporting materials in this paper.

The second stage involved screening. At this stage, out of 2,136 articles eligible to be reviewed, a total of 1,396 articles were removed. The third stage examined eligibility, where the full articles were accessed. After careful examination, a total of 348 articles were excluded due to several factors such as not related to the field of study, not a food staple crop, and not discussing adoption factors. The last stage of review resulted in a total of 392 articles that were used for the qualitative analysis. The screening flow is shown in **Figure 1**.

Data abstraction and analysis

The final 392 articles were obtained for rigorous analysis and assessment. The analysis focused on the types of crops

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TABLE 2 Protocol inclusion and exclusion criteria.

Criterion	Eligibility	Exclusion
Literature type	Journal/Book chapter	Book series, books, conference proceeding
Language	English	Non-English
Timeline	Between 2006 and 2021	<2006
Type of data	Primary data	Secondary data, panel series, systematic review
Crop type	Cereal grain, cassava, yam, potato, plantain	Legumes and beans, non-food crop
Unit of analysis	Farmers	Non-farmers

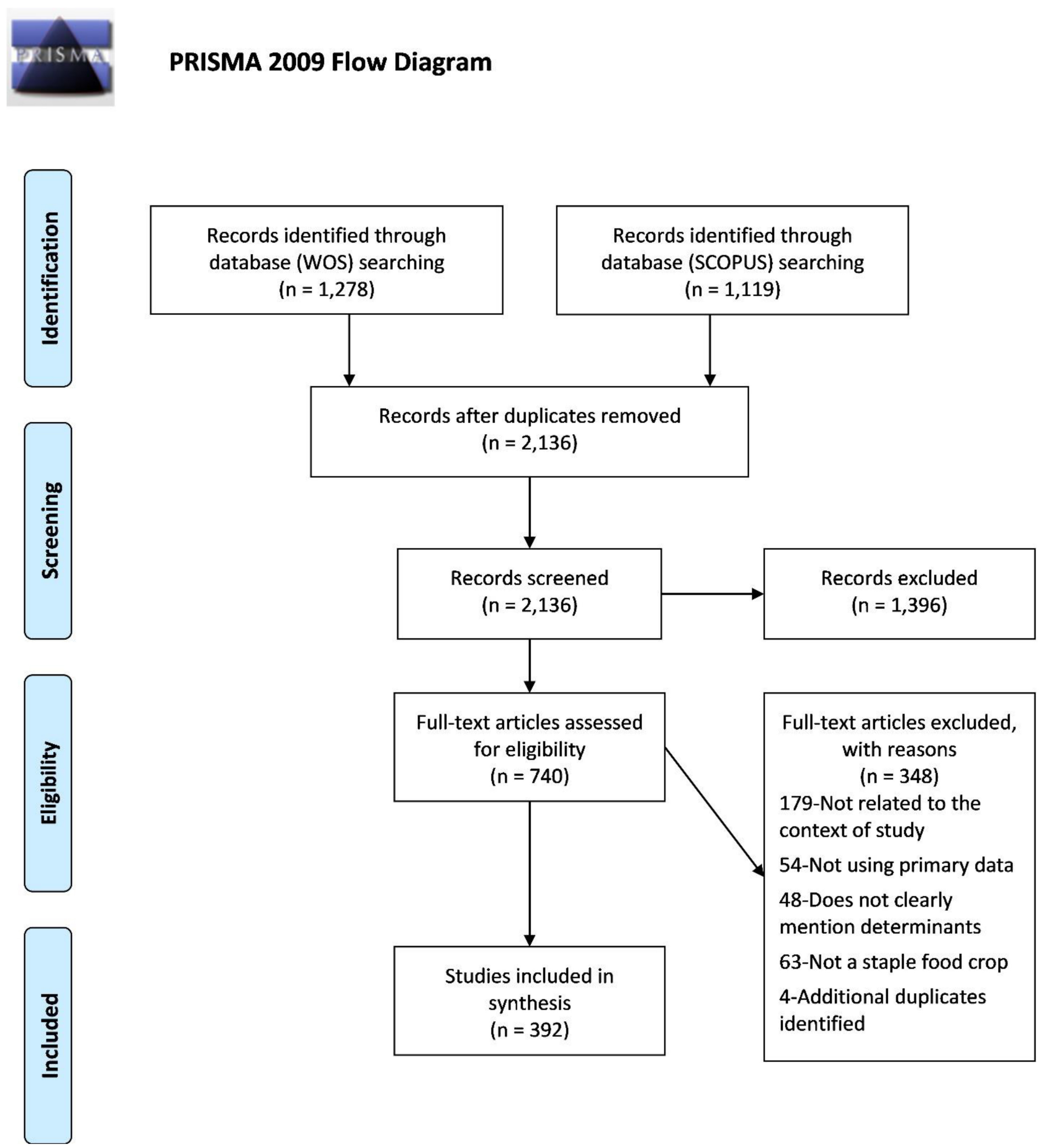

FIGURE 1
PRISMA flow chart. From Moher et al. (24).

and innovations adopted by farmers. Then, the determinants for adoption were identified. The data were extracted by analysing the abstracts, prior to examining the full articles (in-depth), which is essential to identify major determinants and the associate determinants. The qualitative analysis was conducted through content analysis and thematic analysis. It allows categorization of themes and associated sub-themes. The findings will be discussed in the following section.

Results

The review identified the determinants of farmers' decision-making in adopting new technology or innovation in the production of staple food. Generally, a line of studies reported multiple determinants that lead to farmers' adoption of new technology. The review resulted in 4 segments comprising of 12 main determinants and 62 associated determinants (see Figure 2). Three main determinants were identified in the first segment – the farmers' attributes. The determinants are – (1) Education and knowledge; (2) Motivation and participation; (3) Gender and demographics. The second segment is information channel attributes where there are 2 main determinants identified – (1) Extension and training; (2) Communication and information. There are 3 main determinants in the ecosystem and innovation attributes segment which are – (1) Farm profile; (2) Infrastructure and access; (3) Technology and innovation attributes. The structural attributes segment comprises of four main determinants, which are (1) Social structure; (2) Resource needs and support; (3) Institutional factor; (4) Association and organisation.

Table 3 shows main determinants for each segment and the frequency of the determinants being mentioned in the reviewed articles.

Farmers' individual attributes

This first segment comprises of main determinants and associate determinants identified in the reviewed articles related to the determinants associated with the farmers individually. The first main determinant is "education and knowledge". The determinant comprises of several associate determinants such as farmer's background of education which is mentioned 94 times. The other associate determinants are farmers' awareness (26 times), knowledge (41 times) and experience (40 times). The other main determinant in this segment is "motivation and participation". The associate determinant is attitude toward innovation (21 times), motivating factors (5 times), perceived financial benefit (25 times), participation in innovation (18 times), perceived benefit (61 times), perception of risk (28 times), self-interest (3 times) and value co-creation (10 times). The final main determinant for this segment is "gender and demographic" which comprises of age (40 times), general gender factor (39 times), gender of household head (7 times), household size and wealth (19 times) and marital status (2 times).

Ecosystem and innovation attributes

The second segment of this study contains determinants related to the farm, infrastructure and the innovation itself. The first main determinants in this segment are "infrastructure and access". There are 7 associate determinants which are basic farm infrastructure (14 times), farm irrigation (9 times), market accessibility (25 times), farm and plot location (36 times), farm/plot management and condition (18 times), farm system (11 times) and access to technology/innovation (28 times). Besides that, the other main determinant in this segment is "farm profile". The associate determinants are farm/plot size (71 times), land ownership status (32 times) and soil type (6 times). The final main determinants are "technology and innovation attributes" which are divided into 8 associate determinants – compatibility of innovation (14 times), complexity of innovation (10 times), ease of use (7 times), innovation attributes (10 times), observability of innovation (2 times), trialability of innovation (6 times), relative advantage (7 times) and perceived control of innovation (7 times).

Information channel attributes

This segment comprises determinants associated with diffusing information and technique which lead to farmer's adoption of new technology. The first main determinant in this segment is "extension and trainings". The associate determinants are extension services (113 times), farmers school (33 times) and training (50 times). The second main determinant is "communication and information" which comprise communication in general (10 times), communication platform/channel (15 times) and information (32 times).

Structural attributes

The final segment categorized determinants that are related to external factors that are essential and contributed to staple food crop farmers' adoption of new technology. The first main determinant is "resource need and support". Associate-determinants under it are cost of innovation (25 times), access to credit facility (45 times), financial capability (29 times), incentive and subsidy for new technology (21 times), availability of labor (61 times) and off-farm income (12 times). The second main determinants are "social structure" which comprises network trust (14 times), social learning (36 times), social network (36 times), social norm (22 times) and social

FIGURE 2
Summary of determinants of new technology adoption by staple food crop farmers.

TABLE 3 Segment, main determinant and the frequency mentioned in the study.

Segments	Main determinant	Frequency
Farmer's individual attributes	Education and knowledge	201
	Motivation and participation	171
	Gender and demographic	107
Ecosystem and innovation attributes	Farm profile	109
	Infrastructure and access	141
	Technology and innovation attributes	63
Information channel attributes	Extension and training	196
	Communication and information	57
Structural attributes	Social structure	135
	Resource needs and support	193
	Institutional factors	26
	Association and organization	64

capital (27 times). The third main determinant is "institutional factor". It consists of need for policy (17 times), need for regulation (7 times) and power structure (2 times). The final main determinant is "association and organization" which the associate determinants are farmers cooperatives (15 times), membership in farmer association/organization (37 times), leadership (5 times) and partnership with other agency (7 times).

This study identified that there are two (2) most frequently reported crops (see **Figure 3**) which is rice and maize. Drawing on this information, the reported studies and its respected authors based on this categorization is presented in **Table 4** for maize and **Table 5** for rice.

Types of crops, innovations and locations

The findings indicate that there are 11 types of innovation reported in the reviewed articles. Innovations related to sustainable agriculture are the highest (94 articles). It is followed by crop technology (86 articles), farm management and practices (69 articles), climate smart agriculture (37 articles), conservation agriculture (36 articles), smart and digital farming (22 articles), production intensification (20 articles), precision agriculture (12 articles), green technology (6 articles), soil technology (6 articles) and organic farming (4 articles). More than 80% of the reviewed articles reported that their studies were conducted in either Asia or African region. 7.7% of the studies are in North America, 4.8% in Europe, 2.8% in Australia and 2.6% in South America. **Figure 4** shows the types of innovations reported according to the region.

The types of crops reported in the reviewed articles are mostly cereal grain where 38.6% of the studies investigated the adoption of innovation amongst rice farmers. The second most reported crops are maize (36.1%) and followed by wheat (16.5%). The remaining 8.8% of the crops reported are sorghum and teff (2.5%), potatoes (2.5%), cassava and yam (2%), plantain (1.1%) and millet 0.7%. **Figure 3** shows the proportion of crops reported by articles in this study.

Discussion

This paper provides a systematic review on the existing literatures in examining determinants of staple food crops farmers' adoption of new technology or innovation. A rigorous review sourced from two databases has resulted in 392 articles related to determinants of adoption by the staple food crops farmers. The result indicates 4 over-arching segments, 12 major determinants, that comprise of 62 associate determinants. The four segments are farmers, ecosystem, information and structural attributes.

The findings give emphasis on the importance of extension support in promoting adoption of new technology amongst the staple crop farmers. Farmers usually manage their farms based on their personal experience (160, 163, 164). The experience constructs knowledge of farming and is passed from one generation to another. The introduction of new technology or innovation has a learning curve that needs to be achieved by the farmers. Relying on experience alone would not help the farmers to understand or practice any newly introduced innovation. Hence, extension support helps to disseminate information and technique of the new technology or innovation to the farmers. This is in line with other studies that support both extension and education as key factors in determining farmers' adoption of new technology (102, 136).

Enhancing farmers knowledge about new technologies and innovations hence should be promoted from time to time. It is also reported that farmers involved in trainings have a better understanding of the uptake of crop protection techniques and practices which are monumental to increasing production (165, 166). However, it is important to understand that farmers' decision to adopt innovation is also influenced by not only the perceived benefits but also risks. Farmers fear that adopting innovations might increase costs, require more labor or could be detrimental to productivity (163, 167).

Farmers are also seen as learning by observing and imitating peers' action. Social learning hence is one of the factors in determining farmers' adoption of innovation (129, 168). The working mechanism of social learning might be beneficial considering that small farming is regarded as community work. This environment creates a system itself where farmers will be depending on each other for the source of labor, information, capital and support.

The symbiotic relation between farmer's element and social elements can also be seen in the concept of the norm. Interestingly, it is identified that both social norm and gender norm are determinants of farmers' innovation adoption. The prevalence of social norms is reiterated by Fishbein and Ajzen in their Theory of Planned Behavior (169). Several studies adopted and tested this theory where it is reported that farmers adoption of new technology can be explained by the social norm. Farmers do not want to be seen as deviant in their societal norm especially when the technology requires a shift of paradigm in the current method of knowledge. Organic farming and digital farming can be examples of where farmers could have difficulties in leaving their traditional norms. Therefore, it is important for a farming society where norms are paramount to obtain sanction from designated social leaders or institution. If not, Agriculture technology can always be accessible and available to farmers, but the thinking and mindset oriented by culture and religion inversely affect the application [(153), 5].

However, the concept of norms, especially associated with gender, could be affected by the economic practices of various countries. Agriculture and farming activities are usually

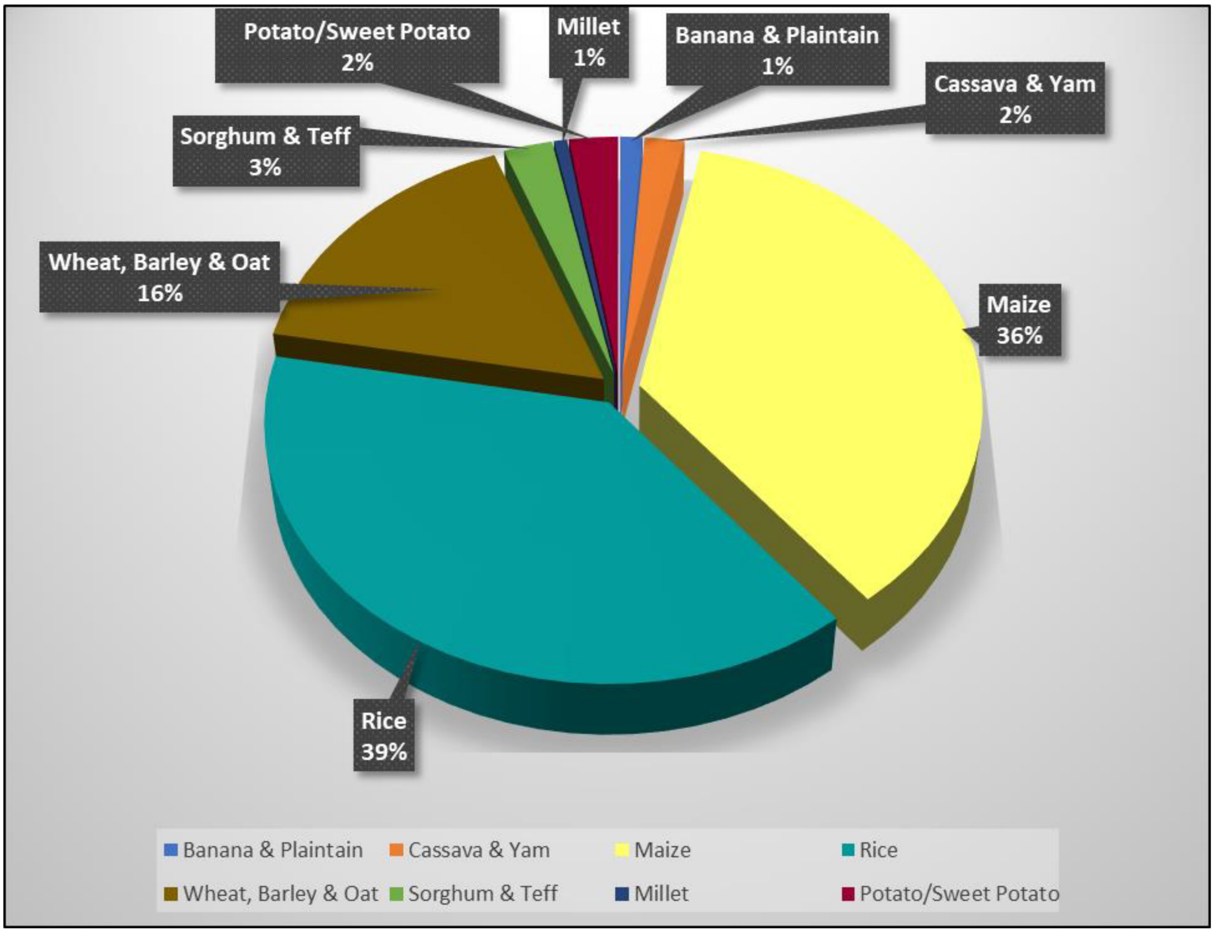

FIGURE 3
Types of crops identified in the reviewed articles.

TABLE 4 Attributes, main determinants and list of reported studies – maize.

Attributes	Major determinants	Authors
Farmers' individual attributes	Education and knowledge	(25–34)
	Motivation and participation	(35–44)
	Gender and demographic	(45–55)
Ecosystem and innovation attributes	Infrastructure and access	(56–61)
	Farm profiles	(62–68)
	Technology and innovation attributes	(69, 70)
Information channel attributes	Communication and information	(71–73)
	Extension and training	(74–84)
Structural attributes	Resource need and support	(85–95)
	Social structure	(9)
	Institutional factor	(96)
	Association and organization	(97–100)

Several studies reported more than one determinant in their findings. The list reported here does not reflects the number of reported determinants in this article.

associated with males dominating the industry. The country's division of labor could however, shift this perception. For instance, in a study conducted in Vietnam, due to the mass migration of male labor to the city, farming activity in the rural region is largely performed by female farmers. Consequently, the decision to adopt new technology is also influenced by gender

TABLE 5 Attributes, main determinants and list of reported studies – rice.

Attributes	Major determinants	Authors
Farmers' individual attributes	Education and knowledge	101–106
	Motivation and participation	107–109
	Gender and demographic	110–118
Ecosystem and innovation attributes	Infrastructure and access	119–122
	Farm profiles	105, 123–125
	Technology and innovation attributes	126–131
Information channel attributes	Communication and information	132, 133
	Extension and training	(134–142)
Structural attributes	Resource need and support	101, 103, 143–146
	Social structure	147–155
	Institutional factor	156, 157
	Association and organization	119, 158–162

Several studies reported more than one determinant in their findings. The list reported here does not reflects the number of reported determinants in this article.

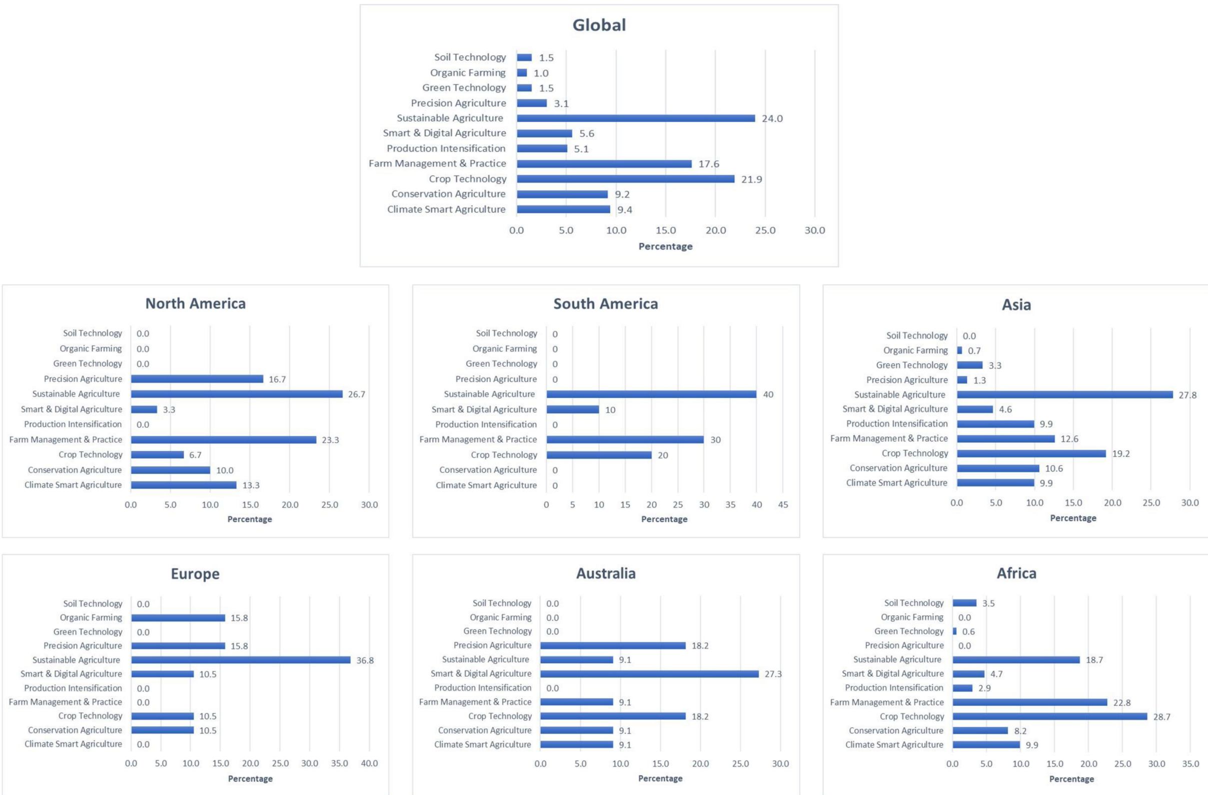

FIGURE 4
Types of innovation and new technologies according to region.

norms (170). The monumental role of women as a decision-maker is also echoed in the other study where it is shown that women play a similar role as men when it comes to deciding in adopting new technology (159).

Besides individual and societal role, government and other authoritative agency play a significant role in farmers' adoption of new technology. Despite low numbers reported in policy and regulation, multiple studies have reported factors such as access to a credit facility, incentive/subsidy, market accessibility as the important one of important determinants. These factors especially related to support and financial assistance are in the realm of authoritative bodies. However, the significant challenges here is identifying and overcoming the void in the roles of governing bodies. Certain government's policy enables subsidy and incentive for farmers to adopt innovation especially when it is in line with their national agenda. For instance, the Malaysian government spend more than 300 million USD on rice subsidy (171). The role of NGOs in helping to reduce farmers burden in adopting new technology has also been reported in several studies (172–174).

The findings of the review reported in this paper strongly suggest that farmers' decision to adopt new technology depends on the availability of basic infrastructure within the farm such as irrigation and accessibility to market (110, 117, 175). Having these basic needs, allow farmers to focus on getting improvement in their production. Another focal point that needs to be highlighted is the ability of farm/plot size as a determinant for farmers' adoption of new technology. It is reported in several studies that farmers with small plot size or small scale farming tend to be more accepting toward new technology or innovation (124, 176, 177). This could be contributed by the fact that farmers with small plots strive to increase their productivity in order to increase revenue. They are unable to enjoy the effect of the "economy of scale" that could be benefitted other large farms.

The analysis of the review also identifies the minimal impact of technology attributes such as complexity, compatibility and ease of use in determining farmers' adoption of new technology. One of the main reasons could be due to the high reliance on extension services and training. With the help from extension officers, farmers have a higher chance to learn about technological attributes for adoption.

Conclusion and future studies

Technology adoption at farms producing staple food crops is essential for the food security but also to improve the livelihood of the farmers themselves. This is crucial especially in countries and communities where their socioeconomic largely depends on the local agricultural production. Furthermore, agricultural yields are also essential to ensure a stable household income as well as to achieve daily caloric intake target and balanced nutrition. Understanding the factors contributing to the adoption of new technology or innovation provides opportunities to increase adoption enhance multiple objectives accordingly such as increase productivity, adaptation to climate, sustainable farming and conservation agriculture. The 64 determinants found in this study has been systematically categorized into 12 major determinants and eventually 4 different segments.

This simplification aims to provide both academics and policymakers with the birds-eye view on the current factors that lead to staple food crops farmers adoption of the new technology. The determinants however, also depend on the targeted demographic profiles. A different demographic profile requires a different approach. Future studies hence should examine the process of disseminating new technology, inclusive of participation, information and communications technology-enhanced, and hands-on experience. Future research should also explore fast expanding areas such as digital farming and green technology.

This paper recognizes the importance of examining the determinants for new technology adoption of staple food crop farmers to overcome current global challenges associated with food security especially during the pandemic. This paper presented the outline and summary of past studies related to innovation adoption by farmers of staple food crop for the past 15 years. Based on the systematic review, 12 major determinants of farmers' adoption have been identified which are education and knowledge, motivation and participation, gender and demographic, farm profile, infrastructure and access, technology and innovation attributes, extension and training, communication and information, social structure, resource needs and support, institutional factors, and association and organization. Types of crops, innovations and locations were also ascertained.

Data availability statement

The original contributions presented in this study are included in the article/**Supplementary material**, further inquiries can be directed to the corresponding author.

Author contributions

AA: conceptualization, writing – original draft, formal analysis, and methodology. SM: supervision, writing – review and editing, and visualization. Both authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fnut.2022.986324/full#supplementary-material

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Improvement in nutritional quality of traditional unleavened flat bread using Quality Protein Maize

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Maize grains are consumed majorly in the form of unleavened flat bread (*chapatti*) in the South East Asian region. The landraces are better accepted for their *chapatti*-making attributes such as grain color and good organoleptic properties. However, these cultivars are low in essential amino acids, particularly lysine and tryptophan content. Hence, an investigation was performed to identify maize genotypes with high nutritional value coupled with good *chapatti*-making qualities. Seven genotypes, comprising two Quality Protein Maize (QPM) hybrids, two normal maize hybrids, and three normal white maize landraces were assessed for their physical characteristics, proximate composition, and *chapatti*-making quality. Landrace 593 showed the highest protein and ash content. Flours obtained from different genotypes were significantly different ($p \leq 0.001$) in terms of protein content, color value, textural, as well as mineral content. PMH 10 and IQMH 203 exhibited the highest and lowest hydration index, respectively. Two QPM hybrids showed significantly higher lysine and tryptophan content as compared to other genotypes. QPM hybrids were identified as the promising material with improved nutritional quality with respect to *chapatti* making. In combination with mustard greens, maize chapatti constitutes an important traditional delicacy in north India. The enhanced nutritional quality of QPM *chapattis* is an added advantage. We show the differentiation of *chapattis* made from QPM and normal maize using a rapid protocol developed previously. This is expected to enable the development and quality control of commercial enterprises based on high protein quality QPM.

KEYWORDS

Quality Protein Maize, landrace, mineral content, amino acid, unleavened flat bread, Indian traditional flat bread, *chapatti*

Introduction

In terms of production, maize is the most important globally and the third most important cereal in India.[1] It is regarded as good for health due to its nutraceutical properties. Celiac disease is an autoimmune chronic illness characterized by small intestine inflammation and villous atrophy (1). Patients with Celiac disease are advised to take gluten-free diets. Therefore, cereal grains such as wheat and barley were excluded from the diet of patients with celiac disease (2, 3). However, it is challenging to adhere to a restrictive gluten-free diet due to various reasons. First, the choice of food becomes limited because cereal products play predominant roles in a daily diet. Second, most processed foods contain gluten-based products as a major or an additional component (4). Moreover, the replacement of gluten is also a technological challenge, as the absence of gluten exhibits quality deficiencies such as poor expansion, color, and texture in final products (5, 6). Hence, the production of gluten-free foods possessing high nutritional value and consumer acceptance can be of immense health benefit to patients with celiac disease.

Maize is one of the preferred gluten-free cereal grains, with suitability to prepare food products mainly addressed to patients with celiac disease (7). Maize flour is consumed as food (35%), mainly in the form of unleavened flat bread ("*chapatti*," also known by the name "*roti*"), in South East Asia. In northern parts of India, especially in the state of Punjab, the combination of maize *chapatti* with mustard green is a very popular traditional dish. Government of Punjab, India, has listed this traditional delicacy in its culture section and has mentioned the availability of entrepreneurial opportunities in cuisine.[2] However, maize is limited in terms of its nutritional properties as being low in essential amino acids such as lysine and tryptophan, which leads to protein-energy malnutrition (5). If biofortified maize is utilized for making traditional delicacies, it would provide the benefits of improved gluten-free, amino acid nutrition. However, the sensory quality and nutritional attributes subsequent to product development need to be ascertained to evaluate its potential deployment.

To overcome malnutrition, the fortification of staple foods such as flatbread was considered (8). To minimize the requirement and to cut the cost of fortification, quality protein maize (QPM) has received much attention owing to its well-balanced protein and also being gluten-free grain, which reduces the risk of various diseases. QPM flour can be used to prepare nutrition-enriched *chapatti* with improved amino acid balances, which can help to overcome the national protein-calorie malnutrition problem (9). Incorporation of QPM flour in common food systems is expected to add value to it, and also provide convenient substitutes to expensive nutritious foods, with the changing lifestyles and trends around the world.

Chapatti has served as a staple diet to a majority of households in India, Pakistan, and some parts of the Middle East (10). Traditionally, it is prepared from wheat flour dough after rolling into a circular sheet followed by baking of both sides at high temperatures for a short time duration, which results in the puffing of *chapatti* by rapid steam formation. The major protein (gluten) present in wheat possesses unique properties to form a cohesive dough, which can trap gases and also enable mechanical sheeting but is not tolerated by patients with celiac disease. Although maize flour is healthy and gluten-free, the absence of gluten results in weak dough-binding properties and affects the *chapatti*-making quality (6). The dough behavior, rheological properties, and sensory qualities such as color, flavor, texture, and aroma of *chapatti* directly affect the acceptability of *chapatti* (11). In India, most of the population consuming maize as food prefers locally available maize landrace for *chapatti* due to its fine texture and unique taste. Keeping in view the preference of people and nutritional aspects, the present study was conducted to evaluate *chapattis* made from different types of maize genotypes, *viz*., landraces, normal, and QPM hybrids. Overall, the study aimed to compare the *chapatti*-making ability and nutritional quality of seven maize genotypes.

Materials and methods

Materials

The materials consist of grains of seven maize genotypes. These genotypes represented both white and yellow maize including landraces, normal hybrids, as well as QPM hybrids.

1 https://www.fao.org/faostat/en
2 https://punjab.gov.in/culture/

Various genotypes were grown at ICAR-IIMR Ladhowal farm, Ludhiana, Punjab. The genotypes were harvested in October 2020 and dried properly followed by storage in airtight containers at ambient temperature. A sample from each genotype was selected randomly. The details of the genotypes selected for the study are as follows:

Sr. No.	Variety	Hybrid	Developing Organization
1	PMH 10	Normal Orange Maize Hybrid	PAU, Ludhiana
2	IQPMH 1708	QPM Experimental Hybrid	ICAR-IIMR, Ludhiana
3	IQMH 203	QPM Hybrid	ICAR-IIMR, Ludhiana
4	MCFL 15	Normal White Maize Landrace	ICAR-IIMR, Ludhiana
5	MCFL 346	Normal White Maize Landrace	ICAR-IIMR, Ludhiana
6	White Hybrid 574	Normal White Maize Experimental Hybrid	ICAR-IIMR, Ludhiana
7	Landrace 593	Normal White Maize Landrace	ICAR-IIMR, Ludhiana

All the grains were screened to remove extraneous matter. The cleaned grains were stored in sealed packages at room temperature. Each genotype was assessed for its physical characteristics and was ground to make maize flour (<200 μ) using a laboratory mill (Perten Instruments, Hagersten, Sweden), sieved, and packed for further analysis and processing.

Analysis of maize kernel, maize flour, and *chapatti* was performed by following methods

Assessment of physical properties of maize kernels

Maize genotypes were assessed for their physical characteristics such as kernel type (flint, dent) and kernel color (white, orange, and yellow), as well as other physical and quality parameters described below.

Thousand kernel weight

Thousand kernel weight was noted by weighing a hundred grains on an electronic weighing balance and multiplied by 10 and results were expressed in grams (g).

Specific gravity

A measuring cylinder (100 ml) was filled with water up to a mark. Pre-weighed corn grains were poured into the cylinder and a rise in the volume of water was noted.

Linear dimensions

The linear dimensions (in triplicates) such as length (L), breadth (b), and thickness (t) of the corn kernel were measured by a vernier caliper (12).

Shape index

The shape index is a measure of the kernel shape that is oval or spherical. The data are computed according to the following equation:

$$Shape\ Index = \frac{l}{\sqrt{b}\, X\, t} \quad (1)$$

where, b = breadth and t = thickness.

If the shape index is greater than 1.5, the kernel is considered oval and if it is less than 1.5, the kernel will be of spherical shape (13).

Hydration capacity (%) and hydration index

Hydration capacity and hydration index were determined according to the method described by Williams et al. (14). To measure hydration capacity, a known weight of grains is transferred into a beaker containing water. Beaker was covered with aluminum foil and left overnight at room temperature. On the next day, the water was drained and the weight of wet grains was noted and calculated as follows:

$$Hydration\ Capacity\ (\%) = \frac{Weight\ after\ Soaking - Weight\ before\ Soaking}{Weight\ of\ Seeds} \quad (2)$$

$$Hydration\ Index = \frac{Hydration\ Capacity\ per\ Seed}{Weight\ of\ one\ seed} \quad (3)$$

Analysis of maize flour

Proximate analysis

Proximate composition of maize flour was determined using the standard method (15).

Moisture content

The moisture content of the flour was analyzed by the hot air oven method after drying at 100°C for 2 h and the percent moisture content is calculated from loss in moisture from the sample (15).

Fat content

Fat content of the flour samples was analyzed by FOSS instrument-Soxtec 2045 (Sweden). Approximately 2 g of flour sample was added in a thimble followed by the addition of petroleum ether (70 ml) in pre-weighed extraction beakers. The instrument was pre-heated prior to analysis at a temperature of 130–135°C. After a pre-determined temperature, extraction beakers were attached and allowed to boil for 20 min followed by rinsing for 20 min. After the solvent was recovered for 10 min, the extraction beakers were removed and weighed after cooling at room temperature. Crude fat (%) was calculated from the increase in the weight of the extraction beaker (15).

Protein content

The protein content of flour samples was determined by the micro-Kjeldahl method. The macro-Kjeldhal method was used to determine the nitrogen content for all raw materials (15). A general composite conversion factor of 6.25 was used to calculate the percent crude protein content.

Ash content

The sample was taken in pre-weighed crucibles followed by charring at a hot plate until no fumes come out. Charred samples were placed in a muffle furnace at 550°C for 5 h and were then placed in the desiccator. The weight of the final crucible is noted as ash content (15).

Carbohydrate content

Carbohydrate content was calculated using a subtraction method, that is, 100 – moisture, ash, fat, and protein contents.

Pasting properties of maize flour

The pasting properties of the maize flour samples were determined by using the Rapid Visco Analyzer (RVA) model starch Master (Newport Scientific, Warrie Wood, Australia). The operation procedure is followed as given below: The RVA was allowed to warm up for 30 min prior to the experiment. The pre-weighed sample was poured into a canister followed by the addition of water (25 ml). The paddle was inserted into the canister and vigorously shaken up and down 10 times through the sample until it mixes properly. Insert the canister into the pre-adjusted instrument. The programmed heating and cooling cycle were given. After the completion of the test, the pasting properties such as peak viscosity, final viscosity, breakdown, and setback were noted. The canister was removed from the instrument and the sample was discarded.

Mineral estimation

The mineral content of maize flour was determined for five different minerals viz. Fe, Zn, Ca, Mg, and K using the OptimaTM2100DV Spectrometer (Perkin Elmer). The mineral concentrations were recorded as ppm, which can be represented as mg of mineral per 100 g of sample.

Amino acid analysis

Amino acid analysis (tryptophan and lysine) of the maize flour samples was carried out by following a previously described method (16).

Color analysis

Color analysis of flour samples was carried out using a Hunter lab colorimeter on the basis of L*, a*, and b* values. The colorimeter was calibrated with the standard black and white plate to set zero. The samples were uniformly packed in clean petri plates. The different places on the surface were given three exposures by the colorimeter. Readings were displayed as a*, b*, and L* where the 'a' value indicates the redness to greenness, the 'b' value measures the blueness to yellowness, while the 'L' value ranges from 0 (black) to 100 (white) which indicates the measure of lightness (17).

Chapatti-making

Preparation of *chapatti*

Chapatti was prepared by adopting the method as described by previous researchers with slight modifications (18). Corn flour was mixed with an optimum amount of lukewarm water to form a smooth dough. Dough balls of similar weight were prepared, placed on a rolling board, and round sheeted using a rolling pin to make *chapatti*. The raw *chapatti* was immediately placed on a hot plate (tawa) and baked at 220°C on one side and then on the other side. It was again turned until fully baked. The *chapattis* prepared from different genotypes (**Figure 1**) were allowed to cool for 10 min at 25°C and then packed in polythene pouches and placed in an airtight container for further analysis.

Physico-chemical properties of *chapatti*

Water absorption capacity

The water absorption capacity of maize flour to form dough was measured by employing the method outlined by Gujral and Gaur (19). The calculated amount of water was added to the flour (200 g) to form the smooth and non-stick dough, appropriate for sheeting without exhibiting any cracks. Then, the optimum amount of water added was noted.

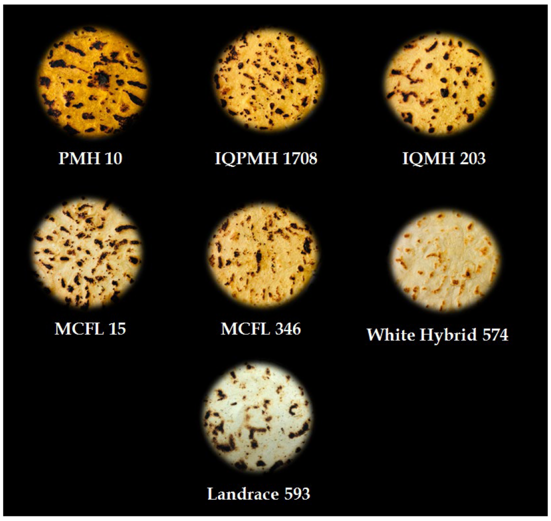

FIGURE 1
Chapattis prepared from different genotypes.

Texture analysis of *chapatti*

A strip of each *chapatti* was tested (in triplicates) for Shear value and Texture Profile Analysis (TPA) on the TA/XT2 Texture analyzer (Stable Micro Systems, Surrey, England) by following the method described below.

Texture Profile Analysis (TPA): Texture Profile Analysis parameters including adhesiveness, cohesiveness, springiness, hardness, chewiness, and gumminess were measured. Samples were cut into uniform sizes and a cylindrical aluminum (P25) probe was used to exert pressure. The instrumental condition used is as follows: Pre-test speed: 10.0 mm/min, Post-test speed: 10.0 mm/min Trigger: 15.0 g, Load cell: 20.0 kg (20).

Shear Value: Shear value was measured by cutting the strip (4 cm × 2 cm) of *chapatti* (taken from the center of the *chapatti*) using Warner Bratzler Blade (HDP/BSK). The following conditions were employed: load cell—50 kg, target mode distance—4.5 mm, pre-test speed—1 mm/s, test speed—2 mm/s, post-test speed—10 mm/s, and trigger force—10 g. The force required to shear the strip of *chapatti* into two pieces was noted. Three measurements were taken for each sample in triplicates and average values are reported (21).

Proximate, amino acid, and mineral content of *chapatti*

Chapatti was analyzed for proximate composition, amino acid content, mineral content, and color as per the previously described methods for flour.

Sensory evaluation

Chapatti prepared from each genotype were analyzed for sensory scores in terms of color, appearance, taste, mouth feel, and overall acceptability in order to find the best genotype for the development of chapatti. Semi-trained and untrained panelists were selected to evaluate the *Chapatti*. *Chapatti* was placed on white paper and labeled with numbers to avoid any bias. A total of 10 semi-trained panelists (five men and five women, between the age group of 25 and 55 years) were selected for sensory evaluation. All the panelists were instructed to rinse their mouths properly with water after tasting every sample and to score the chapatti samples based on the acceptance. A 9-point hedonic scale presenting a score of 1 for extremely disliking and 9 for extremely liking was used. The final score was calculated by averaging the scores provided by all the panelists (22).

Rapid differentiation

A process was designed to rapidly differentiate normal maize grains from QPM grains utilizing molecular differences in the two groups (**Figure 2**). An Indian Patent application (No. 202211015547) has been filed for this process. The same process was used to differentiate between the normal maize *chapattis* from QPM *chapattis*. The method records OD at 595 nm for nutritionally poor protein to act as a proxy for maize protein quality.

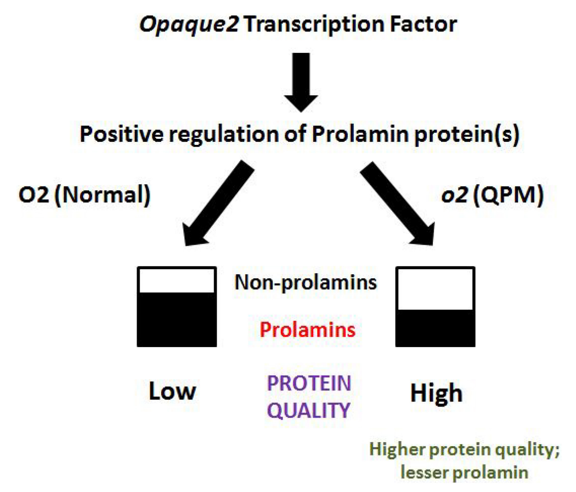

FIGURE 2
Protein quality in normal maize and QPM. By virtue of its replacement by higher quality non-prolamins, the lower expression of prolamins increases protein quality on one hand and decreases the chances of any adverse reactions in some patients with celiac disease as observed in normal maize.

Statistical analysis

Data were recorded in triplicates and presented as mean ± standard deviation. The data were analyzed using SAS version 9.4 software. The least significant difference (LSD) was used as the test for significance for different measured traits among the treatments/genotypes. Paired 't' test was used to test the significant changes in different attributes between maize raw flour and *chapatti* made out of it.

Results and discussion

The physical properties of maize are important for milling and processing industries which usually prefer large grains. The greater the size of grains the more would be the extraction of starch and oil (23).

Physical and dimensional properties of maize kernels

The physical characteristics such as color, grain type, dimensions, thousand kernel weight (TKW), specific gravity, hydration capacity, hydration index, and shape index of different genotypes have been mentioned in **Table 1**. Each of the maize genotypes recorded significantly different thousand kernel weights (TKWs). It was observed that the kernel weight of White Hybrid 574 was highest (368.47 g) followed by Landrace

TABLE 1 Physical and dimensional properties of maize kernels from different genotypes.

	Genotypes	Type	Color	Normal/Opaque	Length (mm)	Breadth (mm)	Thickness (mm)	TKW (gm)	Specific gravity	Hydration index	Shape index
1	PMH 10	Flint	Orange	Normal	11.06 ± 0.48^{A}	8.51 ± 0.35^{B}	4.41 ± 0.33^{B}	291.66 ± 0.50^{E}	0.353 ± 0.004^{C}	0.432 ± 0.002^{A}	1.81 ± 0.07^{AB}
2	IQPMH 1708	Flint	Orange	Opaque	9.45 ± 0.07^{C}	7.2 ± 0.28^{D}	3.90 ± 0.29^{BC}	196.87 ± 0.45^{G}	0.259 ± 0.006^{D}	0.401 ± 0.001^{B}	1.79 ± 0.08^{B}
3	IQMH 203	Flint	Orange	Opaque	9.71 ± 0.10^{C}	7.46 ± 0.56^{CD}	3.46 ± 0.08^{C}	214.20 ± 0.36^{F}	0.273 ± 0.002^{D}	0.194 ± 0.001^{G}	1.91 ± 0.07^{A}
4	MCFL 15	Flint	White	Normal	9.77 ± 0.22^{C}	9.44 ± 0.31^{A}	5.46 ± 0.51^{A}	298.83 ± 0.42^{D}	0.353 ± 0.004^{C}	0.351 ± 0.001^{D}	1.36 ± 0.06^{D}
5	MCFL 346	Dent	White	Normal	10.50 ± 0.21^{B}	9.53 ± 0.25^{A}	5.56 ± 0.23^{A}	322.33 ± 0.89^{C}	0.376 ± 0.001^{B}	0.286 ± 0.031^{F}	1.44 ± 0.07^{CD}
6	White Hybrid 574	Semi-dent	White	Normal	11.28 ± 0.04^{A}	7.88 ± 0.22^{C}	4.40 ± 0.09^{B}	368.47 ± 0.41^{A}	0.380 ± 0.001^{B}	0.331 ± 0.002^{E}	1.92 ± 0.03^{A}
7	Landrace 593	Dent	White	Normal	10.39 ± 0.06^{B}	9.05 ± 0.14^{AB}	5.19 ± 0.32^{A}	356.43 ± 0.85^{B}	0.404 ± 0.002^{A}	0.368 ± 0.001^{C}	1.52 ± 0.05^{C}
	Means Square				1.46***	2.69***	1.93***	130.32***	0.009***	0.019***	0.160***

Values presented as mean ± standard deviation.
Means in the same column with different superscripts ^{abcdefg} are significantly different ($p \leq 0.001$).
The means shown in the same column with common superscripts are not significantly different ($p > 0.05$).
TKW, thousand kernel weight.
***Highly significant at 0.001.

593 (356.43 g), MCFL 346 (322.33 g), MCFL 15 (298.83 g), and PMH 10 (291.66 g). Karthik et al. (13) reported that the TKW of different maize genotypes ranged from 80.50 to 321.85 g, which is in agreement with the present study. Maize genotypes having TKW greater than 290 gm are appropriate for industrial applications because they provide high yields in different products (23). The dimensions such as length, breadth, and thickness of various corn genotypes varied significantly ($p \leq 0.001$) between 9.45 and 11.28 mm, 7.20 and 9.53 mm, and 3.46 and 5.56 mm, respectively. QPM (IQPMH 1708) genotype had the smallest grain size out of the seven genotypes under study. The Thousand Kernel Weight (TKW) of QPM hybrids (HQPM 1 and HQPM 7) was observed to be in the range of 275.5 and 288.3 g by Sangeeta and Grewal (24). The shape index is important in determining the productivity of various genotypes as flat grains are considered desirable grain quality to meet the requirement of high productivity (25). The data showed that two genotypes namely MCFL 15 and MCFL 346 were of spherical shape whereas White Hybrid 574 and IQPMH 1708 showed no significant difference in shape index and were oval-shaped with a higher yield. The study of Srinivas et al. (25) stated that the factors contributing to shaping variation could be the position of grain on the cob, varietal or environmental difference, and distorted or twisted pattern of rows within the cobs. The results of Bolade (26) with respect to TKW, length, and width of the maize ranged from 223.7 to 284.2 g, 9.1 to 11.9 mm, and 8.1 to 9.5 mm, respectively.

The hydration index is a process of water absorption by grains that increases their moisture content and could affect their physicochemical, nutritional, as well as textural properties (27). The hydration index of corn genotypes significantly varied from 0.194 to 0.432 ($p \leq 0.001$). The hydration index was higher in PMH 10 and a lower value was found in IQMH 203. The lower hydration index might help to extend the shelf life of maize grain during storage (27).

Pasting properties of maize flour

The pasting properties of flours obtained from seven genotypes are presented in **Table 2**. A significant difference ($p \leq 0.001$) was observed for pasting properties, *viz.*, peak viscosity (cP), hold viscosity (cP), final viscosity (cP), breakdown (cP), set back (cP), and water absorption capacity (ml) among flours from different maize genotypes depending on the rigidity of starch granules which in turn affect the granule swelling potential (28). Peak viscosity ranged from 207 (IQPMH 1708) to 1,097 cP (PMH 10), indicating the water binding capacity of starch or mixture, which often correlates to the quality of the final product, respectively. The higher peak viscosity may be associated with a high proportion of ungelatinized starch, whereas the lower values might be due to greater degradation through depolymerization and molecular entanglement during processing conditions (29). Breakdown value varied significantly and was higher in MCFL 346 (202 cP) followed by MCFL 15 (117 cP). It is related to the starch response to shear with continuous heating, causing a rupture and resulting in a decrease in viscosity (30). The setback viscosity is related to starch retrogradation and reordering (31) and varied from 908 to 1,696.33 cP. PMH 10 was reported to exhibit a low rate of syneresis and retrogradation of starch molecules (32). The low setback viscosity value of IQPMH 1708 and Landrace 593 flour indicates the lower value of retrogradation. Hence, chapattis prepared from IQPMH 1708 and Landrace 593 genotypes would remain fresh for a longer time (8). Sagbo et al. (33) found the range of peak viscosity and setback viscosity of different maize genotypes varied from 438-1,271.5 cP and 362-2,534 cP, respectively. IQMH-based flour can be used to replace wheat flour for chapatti preparation, which can complement as a source of essential amino acids as well as a gluten-free diet.

Water absorption is the addition of lukewarm water to flour to obtain desired consistency of the dough and indicate the baking quality of the flour. A significant difference was observed for the water absorption capacity of different maize genotypes, however, similar water absorption was observed for MCFL 15 and MCFL 346, and PMH 10 and IQMH 203 (**Table 2**). White hybrid 574 required a higher amount of water (159.3 ml) followed by MCFL 346 (155 ml) for the preparation of dough to make *chapatti,* which could be attributed to the molecular structure of starch, variation in protein content, and presence of high hydrophilic constituents (34). The lowest absorption was found in Landrace 593 ($p \leq 0.001$). It shows that the genotype White hybrid 574 has a higher ability to retain water during the baking process which provides a desirable soft texture in final products (35). However, the QPM genotypes IQPMH 1708 and IQMH 203 had recorded medium water absorption, i.e., 146 and 135 ml. This indicates that this genotype had soaked a good amount of water which is desirable for the baking of *chapattis*.

Nutritional composition of maize flour and *chapattis*

Maize genotypes varied significantly with respect to their proximate composition such as moisture, fat, and protein contents (**Table 3**). The protein content in chapattis was observed to be higher in Landrace 593 followed by MCFL 15. The concentration of protein varied from 6.19 to 8.39% as stated in the previous study conducted by Vaswani et al. (36). MCFL 15 flour had lower moisture (3.02%), and higher ash (1.99%) and crude fiber (1.36%) contents. Sandhu et al. (37) also reported ash, protein, fiber, and carbohydrate contents of 1.66%, 5.18–7.82%, 1.56–2.42%, and 87.6–92.5% for corn flour. The composition of *chapatti* also differed significantly among different genotypes (**Table 3**). The *chapatti* prepared from genotype IQPMH 1708 showed higher moisture content (31.15%), which is a desirable property to impart softness in *chapattis*, whereas MCFL 15-based *chapatti* had lower moisture content (24.67%). IQMH 203-based *chapattis* were recorded for the highest ash (1.71%) and lowest crude fiber (0.18%) contents. The t-value indicates that there was a highly significant difference between maize flours and *chapatti* for the parameters such as moisture (−21.93), fiber (2.79), and carbohydrate (14.09), whereas fat (−0.79), ash (−2.08), and protein (−0.50) showed no significant difference between flour and *chapatti*.

The significantly higher content of minerals such as K (1929.04 ppm) and P (4188.85 ppm) was noticed in IQMH 203 and MCFL 15 genotypes, respectively (**Table 4**). Mineral contents such as copper (2.21–2.36 ppm), zinc (37.05–52.40 ppm), calcium (410–590 ppm), and potassium (2,915–3,471 ppm) were also reported in earlier studies (38). Similar results for Zn content (30.51–42.18 ppm) in maize varieties were also observed by Kabir et al. (39). The difference observed in the mineral composition might be due to the varietal difference, environmental effect, or type of irrigation or fertilizer used. Vaswani et al. (36) stated that the genotypic effect is more

TABLE 2 Pasting properties and water absorption capacity of maize flours from different genotypes.

	Genotypes	Peak viscosity (cP)	Hold viscosity (cP)	Final viscosity (cP)	Breakdown (cP)	Set back (cP)	Water absorption capacity (ml)
1	PMH 10	1097.00^{G}	684.93 ± 1.00^{G}	2410.67 ± 2.52^{G}	92.00 ± 0.00^{G}	1405 ± 2.65^{F}	135 ± 2.16^{D}
2	IQPMH 1708	207.00 ± 2.65^{F}	150.67 ± 2.08^{F}	1058.67 ± 4.04^{F}	48.67 ± 2.08^{E}	908 ± 2.00^{E}	146 ± 0.82^{C}
3	IQMH 203	403.67 ± 5.03^{C}	347.00 ± 4.58^{C}	1808.00 ± 5.57^{C}	57.00 ± 4.36^{D}	1460.67 ± 3.79^{C}	135 ± 0.82^{D}
4	MCFL 15	603.00 ± 2.65^{B}	486.33 ± 0.58^{B}	2088.67 ± 4.04^{B}	117.00 ± 2.65^{B}	1603.33 ± 5.03^{B}	153.6 ± 1.25^{B}
5	MCFL 346	708.00 ± 5.57^{A}	506.33 ± 3.79^{A}	2201.67 ± 4.04^{A}	202.00 ± 4.58^{A}	1696.33 ± 5.13^{A}	155 ± 2.94^{B}
6	White Hybrid 574	298.00 ± 3.61^{D}	283.67 ± 2.52^{D}	1336.33 ± 5.13^{D}	14.00 ± 2.65^{F}	1079.33 ± 4.73^{D}	159.3 ± 1.70^{A}
7	Landrace 593	251.00 ± 2.65^{E}	163.00 ± 3.61^{E}	1071.33 ± 2.52^{E}	88.00 ± 2.65^{C}	908 ± 4.58^{E}	126.3 ± 2.05^{E}
	Mean Square	175223.09***	103245.32***	1451387.64***	14288.19***	791592.52***	463.44***

Values presented as mean ± standard deviation.
Means in the same column with different alphabets in superscript are significantly different ($p \leq 0.001$).
The means shown in the same column with common superscripts are not significantly different ($p > 0.05$).
***Highly significant at 0.001.

TABLE 3 Proximate composition of maize flour and *Chapatti* from different genotypes.

	Flour	Moisture (%)	Fat (%)	Protein (%)	Ash (%)	Fiber (%)	Carbohydrates (%)
1	PMH 10	5.13 ± 0.01^{A}	4.07 ± 0.21^{D}	8.08 ± 0.03^{E}	1.90 ± 0.16^{A}	1.34 ± 0.10^{A}	79.48 ± 0.20^{C}
2	IQPMH 1708	3.43 ± 0.19^{E}	4.57 ± 0.08^{B}	8.47 ± 0.05^{F}	1.28 ± 0.07^{B}	1.10 ± 0.03^{B}	81.15 ± 0.10^{B}
3	IQMH 203	4.21 ± 0.08^{C}	5.13 ± 0.10^{A}	8.38 ± 0.54^{EF}	1.27 ± 0.10^{B}	1.10 ± 0.00^{B}	78.62 ± 0.23^{C}
4	MCFL 15	3.02 ± 0.08^{F}	4.47 ± 0.20^{B}	9.58 ± 0.19^{C}	1.99 ± 0.14^{B}	1.36 ± 0.00^{A}	79.58 ± 0.14^{C}
5	MCFL 346	3.80 ± 0.06^{D}	4.20 ± 0.18^{CD}	8.88 ± 0.03^{D}	1.24 ± 0.04^{B}	1.13 ± 0.01^{B}	80.76 ± 0.25^{B}
6	White Hybrid 574	4.56 ± 0.09^{B}	4.45 ± 0.13^{BC}	10.18 ± 0.04^{B}	1.08 ± 0.05^{B}	1.17 ± 0.00^{B}	78.56 ± 0.19^{C}
7	Landrace 593	3.44 ± 0.04^{E}	4.90 ± 0.10^{E}	10.88 ± 0.03^{A}	0.45 ± 0.58^{C}	1.13 ± 0.01^{B}	79.20 ± 0.70^{A}
	Mean Square	1.62***	5.83***	0.53***	3.25***	0.03***	8.83***
	Chapatti						
1	PMH 10	24.82 ± 0.76^{C}	3.93 ± 0.35^{B}	8.18 ± 0.06^{E}	1.48 ± 0.04^{C}	1.06 ± 0.01^{B}	60.53 ± 0.51^{A}
2	IQPMH 1708	31.15 ± 1.68^{A}	4.57 ± 0.08^{AB}	8.33 ± 0.32^{E}	1.53 ± 0.01^{B}	0.98 ± 0.13^{B}	53.70 ± 1.64^{B}
3	IQMH 203	26.52 ± 3.31^{BC}	4.83 ± 0.56^{A}	9.63 ± 0.26^{C}	1.71 ± 0.01^{A}	0.18 ± 0.00^{D}	58.93 ± 3.32^{A}
4	MCFL 15	24.67 ± 0.52^{C}	4.37 ± 0.37^{AB}	10.05 ± 0.31^{AB}	1.67 ± 0.00^{A}	1.26 ± 0.06^{A}	59.48 ± 0.93^{A}
5	MCFL 346	25.95 ± 2.96^{C}	4.00 ± 0.49^{B}	8.73 ± 0.02^{D}	1.41 ± 0.03^{D}	0.99 ± 0.04^{B}	58.92 ± 2.49^{A}
6	White Hybrid 574	28.27 ± 2.90^{ABC}	4.53 ± 0.12^{AB}	9.95 ± 0.02^{BC}	1.46 ± 0.02^{C}	1.02 ± 0.00^{B}	54.78 ± 2.93^{B}
7	Landrace 593	29.91 ± 0.09^{AB}	4.53 ± 0.47^{AB}	10.38 ± 0.03^{A}	1.36 ± 0.02^{E}	0.55 ± 0.01^{C}	53.27 ± 0.48^{B}
	Mean Square	19.01**	0.31	0.052***	2.38***	0.41***	27.83***
	t Value	−21.93	−0.79	−0.50	−2.08	2.79	14.09
	Pr > |t|	<0.0001	0.4590	0.6326	0.0826	0.0317	<0.0001

Values presented as mean ± standard deviation.
Means in the same column with different alphabets in superscript are significantly different ($p \leq 0.001$).
The means shown in the same column with common superscripts are not significantly different ($p > 0.05$).
***Highly significant at 0.001.

TABLE 4 Mineral and amino acid content of maize flours and *chapatti* prepared from different genotypes.

Flour	Genotypes	Mineral content (ppm)						Amino acid content (gm/100g protein)	
		Zn	Cu	Mn	P	Ca	K	Lysine	Tryptophan
1	PMH 10	38.25 ± 0.23^{B}	2.69 ± 0.09^{B}	6.69 ± 0.05^{B}	3478.35 ± 3.08^{E}	321.46 ± 1.82^{A}	1552.55 ± 1.62^{F}	1.77 ± 0.08^{CD}	0.44 ± 0.02^{CD}
2	IQPMH 1708	28.85 ± 0.11^{C}	2.15 ± 0.03^{CD}	3.90 ± 0.03^{G}	3459.87 ± 3.04^{F}	58.51 ± 1.26^{E}	1917.05 ± 1.02^{B}	4.28 ± 0.14^{B}	1.07 ± 0.04^{B}
3	IQMH 203	35.60 ± 0.06^{B}	2.65 ± 0.04^{B}	5.55 ± 0.03^{D}	4019.35 ± 3.05^{B}	55.00 ± 3.60^{E}	1929.04 ± 1.71^{A}	4.76 ± 0.21^{A}	1.19 ± 0.05^{A}
4	MCFL 15	37.10 ± 1.73^{B}	2.05 ± 0.05^{D}	5.05 ± 0.02^{E}	4188.85 ± 2.73^{A}	133.33 ± 3.78^{B}	1753.54 ± 1.04^{C}	1.64 ± 0.11^{CD}	0.41 ± 0.02^{CD}
5	MCFL 346	30.30 ± 0.11^{C}	2.30 ± 0.14^{C}	6.45 ± 0.03^{C}	3589.52 ± 2.72^{D}	92.66 ± 4.04^{C}	1654.54 ± 2.07^{E}	1.84 ± 0.17^{C}	0.46 ± 0.04^{C}
6	White Hybrid 574	42.77 ± 5.70^{A}	1.55 ± 0.03^{E}	4.45 ± 0.05^{F}	3730.85 ± 5.32^{C}	83.00 ± 2.64^{D}	1524.21 ± 2.99^{G}	1.53 ± 0.12^{DE}	0.38 ± 0.03^{DE}
7	Landrace 593	37.80 ± 0.08^{B}	3.21 ± 0.20^{A}	7.10 ± 0.07^{A}	3736.35 ± 3.50^{C}	92.50 ± 1.97^{C}	1728.54 ± 2.67^{D}	1.39 ± 0.08^{E}	0.35 ± 0.02^{E}
	Mean Square	69.39***	0.86***	4.34***	224549.98***	25821.60**	77164.67***	5.79***	0.36***
Chapatti									
1	PMH10	46.30 ± 0.16^{A}	2.71 ± 0.06^{C}	6.71 ± 0.04^{B}	3339.35 ± 2.05^{F}	491.00 ± 4.35^{A}	1586.55 ± 3.58^{E}	1.64 ± 0.11^{B}	0.41 ± 0.02^{B}
2	IQPMH 1708	41.05 ± 0.19^{C}	3.20 ± 0.04^{AB}	4.50 ± 0.02^{G}	3156.85 ± 3.60^{G}	360.55 ± 6.23^{B}	1931.22 ± 13.79^{A}	4.12 ± 0.07^{A}	1.03 ± 0.02^{A}
3	**IQMH 203**	46.00 ± 0.22^{A}	3.00 ± 0.03^{BC}	6.60 ± 0.02^{C}	3773.85 ± 4.39^{B}	293.66 ± 6.42^{D}	1942.55 ± 3.21^{A}	4.44 ± 0.12^{A}	1.11 ± 0.03^{A}
4	MCFL 15	39.31 ± 0.58^{D}	3.40 ± 0.05^{A}	6.10 ± 0.04^{E}	4128.35 ± 5.56^{A}	333.00 ± 2.64^{C}	1823.05 ± 3.59^{B}	1.40 ± 0.14^{C}	0.35 ± 0.04^{C}
5	MCFL 346	38.10 ± 0.12^{E}	2.26 ± 0.28^{D}	6.48 ± 0.03^{D}	3585.18 ± 2.98^{D}	254.00 ± 3.00^{E}	1701.04 ± 2.62^{D}	1.64 ± 0.08^{B}	0.41 ± 0.02^{B}
6	White Hybrid 574	45.10 ± 0.08^{B}	2.05 ± 0.06^{D}	4.74 ± 0.03^{F}	3629.35 ± 3.54^{C}	219.46 ± 2.70^{F}	1546.72 ± 16.65^{F}	1.80 ± 0.11^{B}	0.45 ± 0.02^{B}
7	Landrace 593	41.45 ± 0.23^{C}	3.51 ± 0.44^{A}	7.40 ± 0.05^{A}	3406.84 ± 2.60^{E}	226.66 ± 4.16^{F}	1763.05 ± 2.54^{C}	1.68 ± 0.11^{B}	0.42 ± 0.02^{B}
	Mean Square	33.07***	0.95***	3.43***	303723.50***	27189.75***	72787.89***	5.36***	0.33***
	t Value	−4.42	−2.61	−2.90	3.57	−8.33	−4.47	0.25	0.24
	Pr > |t|	0.0045	0.0400	0.0273	0.0117	0.0002	0.0042	0.8107	0.8211

Values presented as mean ± standard deviation.
Means in the same column with different alphabets in superscript are significantly different ($p \leq 0.001$).
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***Highly significant at 0.001.

prominent in the composition than other environmental factors. The mineral content of *chapatti* revealed that cooking greatly affects the composition of the minerals. Zn, Cu, Mn, P, Ca, and K contents of *chapatti* varied from 38.10 to 46.30 ppm; 2.05–3.51 ppm; 4.50-7.40 ppm; 3,156.85–4,128.35 ppm; 219.46–491 ppm; and 1,546.72–1,942.55 ppm, respectively. It was observed that the *chapatti* samples had significantly higher Zn, Cu, Mn, Ca, and K contents except for P in comparison to flour samples. It might be due to the cooking process involved during the preparation of *chapatti*. The Zn (46.30 ppm) and Ca (491 ppm) contents of *chapatti* prepared from PMH 10 were much higher.

Lysine and tryptophan contents of maize flours and *chapattis* are summarized in **Table 4**. The lysine and tryptophan contents were observed to be in the range of 1.39–4.76 g and 0.35–1.19 g per 100 g of protein and significantly differed among various genotypes. IQMH 203 showed a higher value of lysine followed by IQPMH 1708. Landrace 593 showed the lowest lysine content which is 1.39 g/100 g of protein. A similar trend in amino acid content was observed in *chapatti* prepared

TABLE 5 Color analysis of maize flour and *chapatti* from different genotypes.

Flour	Genotypes	L*	a*	b*	ΔL	Δa	Δb	ΔE
1	PMH 10	84.88 ± 0.27^{C}	1.48 ± 0.11^{A}	21.85 ± 0.85^{A}	-13.99 ± 0.27^{C}	1.62 ± 0.11^{A}	22.19 ± 0.85^{A}	26.28 ± 0.84^{A}
2	IQPMH 1708	87.38 ± 2.62^{BC}	-0.18 ± 0.05^{C}	14.64 ± 0.61^{B}	-11.55 ± 2.61^{BC}	-0.18 ± 0.10^{CD}	14.98 ± 0.61^{B}	18.98 ± 1.26^{B}
3	IQMH 203	89.18 ± 0.48^{AB}	-0.57 ± 0.03^{E}	13.93 ± 0.22^{B}	-9.69 ± 0.48^{AB}	-0.43 ± 0.03^{E}	14.28 ± 0.22^{B}	17.27 ± 0.18^{C}
4	MCFL 15	88.37 ± 1.79^{AB}	-0.39 ± 0.05^{D}	7.87 ± 0.73^{D}	-10.49 ± 1.77^{AB}	-0.25 ± 0.04^{D}	8.21 ± 0.73^{D}	13.38 ± 1.08^{D}
5	MCFL 346	90.63 ± 0.15^{A}	-0.25 ± 0.03^{C}	9.91 ± 0.41^{C}	-8.24 ± 0.15^{A}	-0.14 ± 0.03^{C}	10.25 ± 0.41^{C}	13.16 ± 0.24^{D}
6	White Hybrid 574	89.85 ± 0.38^{AB}	-0.39 ± 0.06^{D}	7.81 ± 0.57^{D}	-9.02 ± 0.38^{AB}	-0.25 ± 0.06^{CD}	8.15 ± 0.57^{D}	12.16 ± 0.16^{D}
7	Landrace 593	87.31 ± 2.33^{BC}	0.22 ± 0.04^{B}	10.43 ± 0.15^{C}	-11.56 ± 2.33^{BC}	0.36 ± 0.04^{B}	10.77 ± 0.15^{C}	15.85 ± 1.72^{C}
	Mean Square	11.04***	1.48***	74.11***	11.10***	1.52***	74.12***	71.10***
Chapatti								
1	PMH 10	47.09 ± 1.88^{E}	5.31 ± 0.11^{A}	32.23 ± 2.11^{A}	-48.47 ± 6.69^{C}	5.43 ± 0.13^{A}	33.24 ± 2.63^{A}	61.56 ± 1.00^{A}
2	IQPMH 1708	61.78 ± 2.32^{D}	5.23 ± 1.61^{A}	21.11 ± 0.42^{B}	-37.09 ± 2.32^{B}	5.37 ± 1.61^{A}	21.43 ± 0.42^{B}	43.20 ± 2.02^{B}
3	IQMH 203	63.10 ± 1.38^{CD}	4.68 ± 0.58^{AB}	21.20 ± 1.01^{B}	-35.77 ± 1.38^{B}	4.82 ± 0.58^{AB}	21.54 ± 1.01^{B}	42.06 ± 0.89^{B}
4	MCFL 15	69.89 ± 1.67^{B}	3.76 ± 1.66^{ABC}	17.63 ± 0.81^{CD}	-32.65 ± 6.83^{B}	3.24 ± 1.65^{C}	17.97 ± 0.81^{CD}	34.20 ± 1.65^{D}
5	MCFL 346	74.96 ± 1.73^{A}	3.60 ± 0.54^{ABC}	18.42 ± 1.54^{BC}	-29.84 ± 1.97^{AB}	3.75 ± 0.54^{BC}	18.78 ± 1.54^{BC}	35.40 ± 2.42^{CD}
6	White Hybrid 574	68.83 ± 2.05^{B}	2.25 ± 0.79^{C}	15.29 ± 2.69^{D}	-22.92 ± 2.76^{A}	2.98 ± 1.18^{C}	15.63 ± 2.69^{CD}	28.61 ± 2.93^{E}
7	Landrace 593	66.82 ± 4.86^{BC}	2.70 ± 1.9^{BC}	16.25 ± 1.40^{CD}	-31.92 ± 4.64^{B}	3.17 ± 1.94^{C}	15.26 ± 2.78^{D}	37.98 ± 2.51^{C}
	Mean Square	237.50***	4.32***	97.95***	184.08***	3.45***	112.34***	333.34***
	t Value	8.46	−9.18	−12.54	9.83	−10.35	−9.61	−10.84
	Pr > |t|	0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001

Values presented as mean ± standard deviation.
Means in the same column with different alphabets in superscript are significantly different ($p \leq 0.001$).
The means shown in the same column with common superscripts are not significantly different ($p > 0.05$).
***Highly significant at 0.001.

TABLE 6 Sensory attributes and textural properties (Shear Value) of *Chapatti* from different genotypes.

		Sensory attributes				Textural properties
	Genotypes	Color	Aroma	Taste	Overall acceptability	Shear value (N)
1	PMH 10	6 ± 0.00^{AB}	6.3 ± 1.15^{A}	6.3 ± 0.58^{AB}	6 ± 0.5^{A}	4.77 ± 0.52^{C}
2	IQPMH 1708	7.3 ± 0.58^{A}	7 ± 0.00^{A}	7 ± 1.00^{A}	7 ± 0.4^{A}	3.73 ± 0.43^{D}
3	IQMH 203	7.7 ± 1.53^{A}	6 ± 1.73^{AB}	7 ± 1.00^{A}	7 ± 1.4^{A}	4.03 ± 0.42^{CD}
4	MCFL 15	5 ± 1.00^{BC}	4.3 ± 1.15^{BC}	4.7 ± 0.58^{C}	5 ± 0.3^{B}	3.57 ± 0.28^{E}
5	MCFL 346	6.3 ± 1.53^{AB}	3.3 ± 1.15^{C}	5 ± 1.00^{BC}	5 ± 0.4^{B}	5.98 ± 0.77^{B}
6	White Hybrid 574	4 ± 1.73^{C}	5.3 ± 0.58^{AB}	5.7 ± 0.58^{ABC}	5 ± 0.3^{B}	6.96 ± 0.73^{A}
7	Landrace 593	4 ± 0.00^{C}	5.3 ± 0.58^{AB}	5.7 ± 1.53^{ABC}	5 ± 0.6^{B}	3.36 ± 0.21^{D}
	Mean Square	6.63***	4.60***	2.52**	3.19***	6.73***

Values presented as mean ± standard deviation.
Means in the same column with different alphabets in superscript are significantly different ($p \leq 0.001$).
The means shown in the same column with common superscripts are not significantly different ($p > 0.05$).
***Highly significant at 0.001.

from different genotypes. The lysine and tryptophan contents of *chapatti* prepared from QPM hybrids, *viz*., IQPMH 1708 and IQMH 203 were recorded to be 4.12 and 1.03, and 4.44 and 1.11 g/100 g, respectively. However, the lysine and tryptophan contents in *chapatti* were lower as compared to flours which could be due to the effect of baking conditions (40). A study by Gallego-Castillo et al. (41) in non-QPM and QPM-based processed products, namely tortillas, arepas, and mazamorra, showed a true retention value of tryptophan content that is 62.27, 16.67, 15.91%, and 66.29, 23.44, and 19.69%, respectively. During processing, the reduction in lysine content might be due to the occurrence of the Maillard reaction, which modifies the starch and protein structures and leads to more availability of reducing sugars and reactive sites of protein, respectively (42). It was also found that the lysine and tryptophan contents are more than double in the QPM-based *chapattis* as compared to normal and landrace genotypes-based *chapattis*. Hence, *chapattis* prepared from QPM genotypes are more nutritious and beneficial for human consumption than chapattis prepared from normal maize.

Color parameter of *chapatti*

Hunter color laboratory parameters such as L*, a*, and b* values among flours and chapattis prepared from different maize genotypes were observed (**Table 5**). The L* value of flour and *chapatti* from different maize genotypes significantly varied from 84.88 to 90.63 and 47.09–74.96, respectively. In the case of flour and *chapattis*, the highest L * value (lightness) was observed for MCFL 346 and the lowest for PMH 10. L* values of IQPMH 1708 and IQMH 203 were observed to be 87.38 and 89.18 indicating that the color of *chapattis* was acceptable and preferred by the consumer. L* value of 81.94 to 86.96 for corn flours from various genotypes have been reported by Sandhu et al. (37). Kathuria et al. (43) analyzed the color value of maize flour to be around 70.05 ± 0.02. The a* value presents the redness or greenness which ranged from −0.57 to 1.48 and 2.25–5.31 in flour and chapatti, respectively. The highest a* and b* values in PMH 10-based flour and *chapatti* might be due to the high level of anthocyanins and carotenoids, respectively (17). ΔL, Δa, Δb, and ΔE values indicate the color difference for lightness, redness-greenness, blueness-yellowness, and total color difference, respectively, for different genotypes-based corn flour and these values ranged from −13.99 to −8.24, −0.43 to 1.62, 8.15 to 22.19, and 12.16 to 26.28, respectively. Genotypes, *viz*., White Hybrid 574, MCFL 15, and MCFL 346 exhibited no significant difference in total color difference value. IQMH 203 and IQPMH 1708 were not significantly different with respect to the b* value in maize flours. Highly significant differences for parameters such as L (8.46), a*(−9.18), b* (−12.54), ΔL (9.83), Δa (−10.35), Δb (−9.61), and ΔE (−10.84) were observed among corn flours and *chapatti* for different genotypes.

Textural properties of *chapatti*

The textural properties directly affect the overall acceptability of *chapatti* (20). The results indicated that the different maize genotypes exhibited significant differences in the shear force of the *chapatti*. The shear force value is mainly related to the freshness and pliability of the final product. The value of shear force was found to be in the range of 3.36 (Landrace 593) − 6.96 N (White hybrid 574), (**Table 6**). A decrease in shear force resulted in an increase in pliability and soft texture which might be due to the higher retention of moisture in *chapatti* (20).

Sensory attributes of maize-based *chapatti*

The sensory score of *chapatti* made from various maize genotypes is elucidated in **Table 6**. Maize *chapatti* prepared from IQMH 203 and IQPMH 1708 was rated highest in terms of color, taste, aroma, and overall acceptability and were not significantly different from each other. *Chapatti* prepared from White Hybrid 574 and Landrace 593 was not highly acceptable in terms of sensory attributes. Hence, due to the relatively higher sensory score of IQMH 203 and IQPMH 1708 coupled with their relative nutritional value in terms of mineral profile and essential amino acids, they were considered the most appropriate varieties for the production of maize-based nutritious flat breads.

Differentiation of QPM *chapattis* from normal maize

Figure 2 provides a schematic representation of the mechanism, by which QPM results in higher protein quality as compared to normal maize. *The opaque-2* gene positively regulates low-quality prolamin proteins in normal maize, whereas its mutation in QPM increases higher-quality non-prolamin proteins, including albumins, globulins, and glutelins. By virtue of its replacement by higher quality non-prolamins, the lower expression of prolamins increases protein quality on one hand and decreases the chances of any adverse reactions in some patients with celiac disease as observed in normal maize (44). In order to enable commercialization of the biofortified products in the market, it is necessary to employ a rapid method for Quality Control and consumer empowerment. Using a previously standardized process (Indian patent applied), we quantified protein quality in *chapattis* made from normal maize and QPM. The samples were read at 595 nm after processing. A lower value indicates less nutritionally poor protein fraction, thereby higher overall maize protein quality. Conversely, a higher amount of nutritionally poor protein indicates overall lower maize protein quality. The readings of IQPMH 1708 and IQMH 203 at 595 nm were 0.135 and 0.152, respectively, while the readings for normal genotypes were above 0.25. This indicates that a cut-off of 0.2 at 595 nm is indicative of protein quality in maize chapattis. This process requires less than 10 min to complete, providing a good tool for the quality control of the product.

Conclusion

With respect to modern lifestyles and healthy eating trends, traditional and nutritional food products are gaining popularity. *Chapatti* is a major staple baked food in most households and could bring the combination of nutrition and goodness of maize. Hence, the present study was executed for a better understanding of the nutritional and chapatti-making quality attributes of different maize genotypes. C*hapatti*s prepared from QPM showed higher lysine and tryptophan content as compared to other genotypes. The overall quality score of *chapatti* prepared from IQMH 203 and IQPMH 1708 scored higher and imparted a desirable aroma coupled with *chapatti* of better texture, taste, and acceptability. Therefore, such cultivars need to be popularized for nutritional security at low cost in midday meals and other nutrition schemes of the government as well as for catering to patients with celiac disease. Given the listing of maize *chapatti* in traditional delicacies, there is ample scope for entrepreneurship development in this sector using QPM. The availability of a rapid protocol to differentiate the products made from QPM from those of normal maize is an added advantage to ensure quality control and empower consumers. Overall, the study provides a comparative assessment of different maize types for *chapatti*-making and shows the ability of rapid differentiation to categorize and confirm the final product based on protein quality.

Data availability statement

The original contributions presented in this study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

NK performed the experiments and prepared the manuscript. RK planned the experiments and reviewed the manuscript. AS performed the experiments on Rapid Kit and reviewed the manuscript. DS and DC reviewed the manuscript. BS planned the experiments. AD analyzed the results. PK and YK performed the experiments. PS performed the mineral content analysis. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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Impacts of urban safety net on income, food expenditure and intake capacity of poor households in Addis Ababa city, Ethiopia, 2021

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Although measures taken to address food insecurity and income inequality showed notable outcomes, they have continued to be major global issues mainly in urban areas of developing countries. To relieve these problems, Ethiopia started an urban safety net program in Addis Ababa city in 2017. The purpose of this study was to investigate the impacts and progress of the urban safety net program, mainly its cash transfers (CTs) on income, consumption, and food security of poor households using indicators based on elements of a theory of change and Engel's coefficient. It assessed whether the program was significant (or not) to program beneficiaries compared to situations before the start of the program, non-beneficiaries, and beneficiaries' sex. A total of 560 sample households were selected through a multi-stage sampling for household surveys. Comparative approaches, paired and independent *t*-tests, and linear regression were used to analyze the data. Results revealed that the CTs had a satisfactory targeting accuracy of the poor and produced positive effects on monthly income, savings, food expenditures and intake, and seed money for a business start. Since financial transfers account for a larger proportion of the income of households, current income becomes significantly bigger compared to income during the pre-program periods and non-beneficiary households. Food access, expenditure, and savings capacities of beneficiaries in post-CT became better than in pre-CT along with better food access and diet intake two to three a day than non-beneficiaries. Besides, coverage and benefits were statistically significant for women compared to men. The implementation of the urban safety net program is good in its positive impacts and progress toward nutrition and food security of poor households as a result of an increase in their income, food expenditure, intake, and access. This implies policymakers could potentially expect to see improvements in nutrition and food security, especially when targeting urban poor and female-headed households. However, delays in payments and work equipment, declining size and value of payments, and weak supplementary services are the program's shortcomings. Policy implications to improve the size of transfers, emergency aids, timely payments and equipment provisions, and interventions like regular business training, supervision, and guidance are recommended.

KEYWORDS

urban safety-net, impact analysis, performance indicators, food security, theory of change, urban planning

Introduction

These days, poverty rates around the world, and developing countries, in particular, are higher, mainly because urban poverty rates are quite high in large cities. In the face of continued poverty, limited income and household purchasing capacity have reshaped the current focus once again on food insecurity, mainly in middle and low-income countries. As a form of the productive safety net program (PSNP) and recently as an alternative to food aid, cash transfers (CTs) have been introduced as an instrument for food security in these countries. Existing literature showed the impact of CTs on hunger has been most pronounced in low-income countries where poverty is generally more severe (Blattman et al., 2013; Green et al., 2015).

In these settings, households receiving additional income are particularly likely to prioritize spending on improving the quantity and/or quality of food consumed. Cash transfers play a significant role to smooth food consumption and directly improve the quality and diversity of diet through increased and stabilized household income. Cash transfers may also improve the availability, access, and utilization of food for households (Attanasio et al., 2005; Arnold and Conway, 2011).

Like many countries in the developing world, the urban-rural poverty rate differential in Ethiopia is low in comparison to other countries. The total national poverty rate in 2011 was 29.6% (30.4% in rural Ethiopia and 25.7% in urban areas). The poverty gap index is estimated to be 8% in rural and 6.9% in urban Ethiopia (World Bank, 2015).

Food insecurity, income inequality, and poverty are the major underlying global themes in the Sustainable Development Goals (SDGs). Ending these problems has therefore continued to receive more attention in monitoring the progress of Sustainable Development Goal (SDG) targets (Haddad et al., 2015; Welteji et al., 2017). This holds for Ethiopia where poverty, food security, and low income, mainly among women, remain a central problem; about 27% of women of reproductive age are chronically malnourished (Blattman et al., 2014; Devereux et al., 2014; CSA ICF International, 2015).

Abbreviations: AABoFED, Addis Ababa City Bureau of Finance and Economic Development, Ethiopia; ASPIRE, Atlas of Social Protection: Indicators of Resilience and Equity; CTs, Cash Transfers; CCTs, Conditional Cash Transfers; CSA, Central Statistical Agency, Ethiopia; ETB, Ethiopian Birr; FAO, Food and Agriculture Organization; FGDs, Focus Group Discussions; GoE, Government of Ethiopia; HHs, Households; HLPE, High Level Panel of Experts on Food Security; ICF, Inter Container-Interfrigo International; IEG, Independent Evaluation Group; MoA, Ministry of Agriculture, Ethiopia; MoUDH, Ministry of Urban Development and Housing, Ethiopia; PPP, Per capita Purchasing Power; PWP, Public Works Program; UFSS, Urban Food Security Strategy; UJFSA, Urban Job Creation and Food Security Agency; USD, United States Dollar; WB, World Bank.

Addis Ababa's poverty rate is as high as 28.1%. From 2005 to 2011, consumption growth was negative for the poorest 15% of the urban population and the majority of Addis Ababa households, as wages did not rise to compensate households for rising food prices. In large cities like Addis Ababa, poverty has been falling, but not as fast as in rural areas and smaller urban centers. One-fifth of Ethiopia's urban population lives in Addis Ababa and reducing poverty rates in this city is a key priority (CSA ICF International, 2015; World Bank, 2015, 2018).

To alleviate this problem, the government of Ethiopia developed the Urban Food Security Strategy (UFSS) in 2015 through safety net programs. The objective of the strategy was to alleviate urban food insecurity and address the increasing levels of vulnerability, inequalities, and poverty. This was expected to be achieved over a long-term period through a gradual roll-out plan in different phases, starting with big cities that have a population of over 100,000 people (PSNP, 2014).

In Ethiopia, productive safety net programs started a long time ago and have achieved these goals mainly in rural parts of the country (Camilla et al., 2011). However, such programs are relatively new for urban areas and were implemented recently in 2017 (PSNP, 2014; Shigute et al., 2019). In this regard, Ethiopia's PSNP has a critical role in advancing food and nutrition security and livelihood targets of SDG 1, mainly for vulnerable communities such as women, the elderly, people with disabilities, and children (Burchi and Strupat, 2016; FAO, 2017).

The urban safety net program, which is the first of its kind in urban areas, is a 5-year phase-by-phase government program targeting 11 major cities in Ethiopia using a program Implementation Manual (PIM). This manual has benefited from the country's experience in delivering a rural productive safety net over the past 10 years. It is designed to facilitate the implementation and management of the program and to provide guidelines and operating procedures that will assist the key implementing institutions, mainly the Ministry of Urban Development and Housing (MoUDH), the Urban Job Creation and Food Security Agency (UJFSA), the Ministry of Labor and Social Affairs, and other relevant agencies including regional and city administrations and municipalities (Gilligan et al., 2008).

The urban safety net initiatives are being implemented in several developing countries, including Ethiopia, to benefit individuals and households who are food insecure, unable to work, or are experiencing a temporary decline in purchasing power by providing them with income. Such initiatives include cash transfer programs, subsidies, and labor-intensive public works projects. The urban safety net program was started to enable poor households or individuals to generate seed money (or initial capital) to begin new businesses and get involved in small and micro-enterprises, which are important steps toward the achievement of sustainable livelihood and food security (Ministry of Agriculture, 2014; World Bank, 2015; GoE, 2016).

In recent years, several studies (Attanasio et al., 2005; Arnold and Conway, 2011; Blattman et al., 2013; Burchi and Strupat, 2016; World Bank, 2018) have appeared focusing on safety net initiatives entirely from an African context. Almost all extant research on safety net in Ethiopia (Gilligan et al., 2008; Camilla et al., 2011; Devereux et al., 2014; Ministry of Agriculture, 2014; PSNP, 2014; Welteji et al., 2017; Shigute et al., 2019) exclusively focus on rural households without addressing similar impacts on urban households. In Ethiopia, unlike the safety net programs in rural areas, cash transfers (CTs) are the main intervention within urban PSNP, and it is a recent phenomenon which was rolled out by the government in collaboration with the World Bank in 2017 in Addis Ababa, where two-thirds of the country's poor households are found (GoE, 2016).

The most immediate impacts of CTs are expected to be an increase in income, food access, and consumption for poor or low-income households in urban areas. However, much is not known about the effects and roles of these CTs from the perspective of households in urban areas. There is also limited knowledge and evidence on the gendered dimensions of the CT programs, particularly on whether they contribute more to women's income, food purchasing capacity, and empowerment than men comparatively. The cash transfers started in urban areas and their impacts on monthly income, food security, and nutrition are unknown and they remain unexplored topics in previous studies.

Thus, a critical evaluation and examination is urgently needed to determine whether the urban safety net program implementation is practically productive and does it enhance the income, food expenditure, and intake capacity of program beneficiaries, particularly the poor and women-headed households. This research is motivated to explore the impacts of safety net which is a recent phenomenon in urban areas and identify further research and policy implications.

The debatable issues among scholars and literature on the helpfulness of safety net in urban areas relative to rural areas, the effectiveness of cash transfers in comparison to in-kind aid, and its effects on female-headed households compared to male-headed households inspired this study. This study, therefore, aims to explore the extent to which urban PSNP, particularly cash transfers, improve food security and nutrition at the household level in Addis Ababa, Ethiopia.

Given this research is almost the first of its kind focusing on urban or non-farmer households' in Ethiopia, it was also motivated to offer evidence-based responses to key questions regarding the performance, impacts, roles, and challenges of the PSNP particularly the CTs since 2017. It does this by examining the theoretical pathways advocating cash transfers as measures that can contribute to alleviating the level of household income, savings, food items purchasing, and intake capacity, as well as a diversity of diets. As a result, these were used as indicators to determine the level of household food security and nutrition improvements such as access, availability, and utilization of food.

To achieve the objectives, a modeling framework, composed of four steps, was undertaken. Initially, a preliminary analysis was done to determine the implementation and performance level of the CT program using parameters such as targeting accuracy, adequacy, generosity, and benefit incidence of CTs. Second, the research applied the theory of change and Engel's law as a theoretical foundation to identify relevant indicators, measures, and hypotheses regarding the impacts of CTs. Accordingly, the following four hypotheses were developed to guide the content of this study.

- Cash transfers have improved monthly income, food purchasing and intake capacity, and the variety and number of daily diets of poor households.
- Through CTs, the increased incomes have contributed to the improvement of food consumption and security of poor urban households.
- The observed benefits are more substantial to program beneficiary households compared to situations in periods before the start of the program and relative to non-beneficiary households.
- The benefits related to monthly income, food purchasing, intake capacity, and variety of diets are also more significant in female beneficiary households than their counterparts.

Third, the study adopted a conceptual framework that outlines the impacts and pathways of cash transfer on household income and basic components of food security. Lastly, "with and without" and pre/post impact evaluation designs, paired samples and independent samples *t*-tests, and Mann-Whitney linear and binary logistic regression models were applied to estimate, model, and evaluate the impact of the CTs. These were also used to verify the extent to which the theoretical claims or assumptions of the change theory and Engel's law contribute in practice in the context of low-income urban households.

Thus, this paper contributes to the existing literature and body of knowledge on the impacts of CTs on household food security. This study can fill the knowledge and literature gap by offering an urban perspective and by analyzing the debatable issues on the effectiveness of cash transfers in comparison to in-kind aid and its effects on women relative to men beneficiaries. It provides a more in-depth analysis by using homogeneous and consistently measured variables to explore the differential effects of CTs on a range of outcomes on food security and nutrition. Thus, it can inform the recent developments, trends, new challenges, and opportunities for policymakers and planners in designing innovative pathways to enhance the safety net program and address income inequalities and food insecurity in urban areas. Concerning methodological contribution, the author employed theory-based, latest, multi-criteria, and statistical analysis to estimate a continuous relationship between the CTs, household income, food purchasing capacity, and food security.

In general, the objective of this study is to examine the implication and impacts of urban PSNP, particularly cash transfers, on food security and nutrition of program beneficiary households. More specifically, it explored the extent to which monthly incomes, saving practices, food purchasing capacity, and daily food or nutrition intakes are enhanced and how the challenges are impeding the program implementation and goals.

Review of the literature

Role of cash transfers in household food security: Theory and evidence

A review of related literature was carried out for theoretical and empirical evidence based on the leading research question: "Are urban PSNP mainly cash transfer programs capable of contributing to the income, food consumption, and food security of poor households?" The Public Works Program (PWP) is a commonly used social protection or safety net instrument to provide support, mainly cash transfers, to working-aged people who are poor, unemployed, or underemployed and working in jobs that have low productivity (Anna, 2013). Cash transfers are an increasingly popular social protection mechanism used by many developing countries to improve food security and the nutritional status of lower socio-economic groups. The overall objective of the program can, therefore, be seen as preventing the intergenerational transmission of poverty. The major type of CT programs that has been used mostly in developing countries is conditional CT (CCT). The number and size of CTs have increased noticeably in the last 20 years (Honorati et al., 2015).

To receive assistance, a conditional cash transfer program requires beneficiaries to undertake a specific activity, such as public works or training. After the condition is fulfilled, CTs are given to poor and vulnerable people with no restrictions on how the cash is to be spent and no requirements beyond meeting the eligibility criteria, for example, being poor. Conditional cash transfers focus on human capital development and usually target households with children of primary or secondary school age (Pega et al., 2015).

Thus, CCTs are widely designed to achieve the objective of reduction of short-term food insecurity by improving low-income households' immediate consumption levels and nutritional status (FAO, 2008; HLPE, 2012). Household food security is the condition when all people at all times have access to sufficient, safe, and nutritious food. It is also defined by the availability of household resources to purchase adequate food for all family members, particularly by cash income. Spending on food, the amount and diversity of diets, food frequency, consumption behaviors, and experience of food insecurity are the most common measures of household food security (Smith and Haddad, 2002).

Engle's coefficient and theory of change is commonly used to explain the internal logic of an intervention (i.e., CTs for increased income, food purchasing capacity, and food security) and to hypothesize cause and effect links. As indicated in the conceptual framework, key assumptions of these theories are used to explain the sequence of changes, such as "impact pathways" or "outcomes chain". Engel's Law indicates that lower-income households spend a greater proportion of their income on food than households with a middle or higher income. As food costs increase, the percentage spent by lower-income households is also likely to increase. Focusing on a single activity, i.e., a cash transfer program, this study explored statements of change such as: "If we take 'x' action, then 'y' change will result, because..." These statements were discussed within the context of the program, and subsequently, evidence was sought to support them (Ober, 2012).

Both theories helped to identify evaluation questions or key hypotheses, undertake context analysis, explore assumptions and how the intervention worked (i.e., CTs), test the hypotheses, and assess evidence for the hypotheses. The PSNP's CT component has the potential to result in various benefits. By increasing household income, cash transfers can theoretically contribute to food security and consumption. This is because increased household income can increase food availability and access to food for the poorest households directly by enabling households to purchase food and by increasing household actual and share of expenditure on food. Increased household income can also increase food utilization and nutrition directly by improving the number, quality, and diversity of daily meals, resulting in improved nutritional status (Smith and Haddad, 2002; Arnold and Conway, 2011). Cash transfers that are implemented as part of a broader package of interventions linking beneficiaries to supplementary services such as knowledge, information, safety, and nutritional supplements have also addressed other causes of malnutrition and intra-household inequalities, mainly through women's empowerment (Yoong et al., 2012; Hagen-Zanker et al., 2017).

Recent studies (Haushofer and Shapiro, 2013; IEG, 2014; Bastagli et al., 2019) show that CTs may also directly affect intra-household dynamics. If the transfer is distributed to the female heads of households, they are better able to advocate for their preferences as a result of controlling more resources. As the majority of households' income is spent on food in many developing countries, food security improved as a result of receiving CTs. Households receiving CTs had better dietary diversity than those receiving food, suggesting that CTs may be more effective. This is because cash transfers give dignity, choice, and flexibility to affected populations and therefore play a key role in achieving nutrition security for all (Gilligan et al., 2008).

According to Attanasio et al. (2005), the increased income allowed households to overcome credit and saving constraints, and households became willing to take on more profitable investments if the regular income was reliable. It also indicated that, through increasing household income, the positive impact of CTs on hunger and food security has been most evident in low-income countries, where poverty is commonly harsher. Similarly, food consumption and food security of over seven million rural people who were previously dependent on relief have been improved by the Productive Safety Nets Program in Ethiopia (Gilligan et al., 2008; Baye et al., 2014).

However, the impact and contribution of such kinds of PSNP to household food consumption and food security in urban areas of Ethiopia and Africa have not been adequately studied. Thus, the gap in research, literature, and recent knowledge on this particular topic has motivated the author to conduct this study.

Conceptual framework

There are numerous approaches used to hypothesize and model the linkages between CTs and their impacts on food consumption and security. However, for this study, the appropriate approach is to use CTs as a starting point or input and conceptualize the different impacts at the individual and household levels, with one of the potential impacts being food and nutritional status. This approach is more useful for the contextualization and better identification of how CTs can affect the core causes or pillars of food security and therefore the pathways of impact. This conceptual framework's approach is also relevant to key assumptions of the theory of change (ToC) and Engle's coefficient.

When looking at the evidence on how cash transfer programs affect income, food security, and nutritional outcomes and impacts, it is important to distinguish between the outputs, outcomes, and impacts of CT programs. The author explored the reasons behind the findings shown in this paper after making impact evaluations and discussing the extent to which the evidence supports the theoretical assumptions on the role of CTs in contributing to household food security by looking at the output, outcomes, and impacts in the conceptual framework shown in Figure 1.

The key criteria and pillars of food security include households' economic and physical access to food; food utilization, which is the proper uptake of nutrients in the body through consumption; availability of food determined by business and food production; and stability of the other three dimensions over time (Smith and Haddad, 2002; FAO, 2008).

The conceptual framework in Figure 1 shows that CTs potentially have an impact on all pillars of household food security. Through increased income and purchasing capacity, households may invest in their businesses and increase household-level food access and utilization. Households with increased economic access to food are capable of purchasing more food and more diversified products. Finally, a consistent household income may improve and stabilize food consumption and security over time (Maxwell et al., 2013).

In this conceptual framework, the pathway through which CTs may contribute to the basic output, outcome, and impact is by making additional financial resources available for food security. Accordingly, CTs directly increase household income and, consequently, the resources available for household food security. When households use their cash and income to buy more or better food or to invest in a business or productive assets, they improve both their food security and their diet diversity (Gertler et al., 2006; Adato and Bassett, 2009).

Materials and methods

Description of the study area

Addis Ababa is the capital city of Ethiopia, Africa. Its population is estimated to be close to five million. Though it is the capital of the country and the seat of major commercial operations, 30% of its population is under the poverty line, which is slightly higher than the national average. About 26.1% of the residents face food poverty and women, more than men, are affected by poverty. Overall, 48.7% of Addis Ababa residents are poor or vulnerable to poverty and income inequality; the Gini coefficient of real consumption per capita for the year 2015 was estimated to be 0.32, which is quite low compared to many other cities. As indicated on the map of the study areas in Figure 2, there are ten sub-cities in the Addis Ababa city administration. Under each sub-city administration, there are "woredas" or districts which are the lowest units of administration. For example, Bole and Yeka sub-cities are arranged into 14 and 13 woredas (or districts) under their jurisdiction, respectively. According to the data obtained from food security offices, there are about 2045 and 2019 food-insecure and safety net program first-round beneficiary households in Yeka and Bole, respectively (AABoFED, 2015; Ethiopian Mapping Agency, 2019).

Site selection and sampling technique

Using a multi-stage sampling technique, both probability and non-probability sampling were employed to select households for the collection of cross-sectional data through household and community surveys. In the first stage, Addis Ababa was purposefully chosen among 11 other recipient cities targeted by the program because it accounts for about one-third of the poor and food-insecure households and PSNP program beneficiaries in the country. At full capacity, the program aims to benefit close to 604,000 people in two rounds, with about 200,000 people (almost one-third) from Addis Ababa (AABoFED, 2015).

In the second stage, due to the homogenous nature of the CT program beneficiary households in all ten sub-cities of the city,

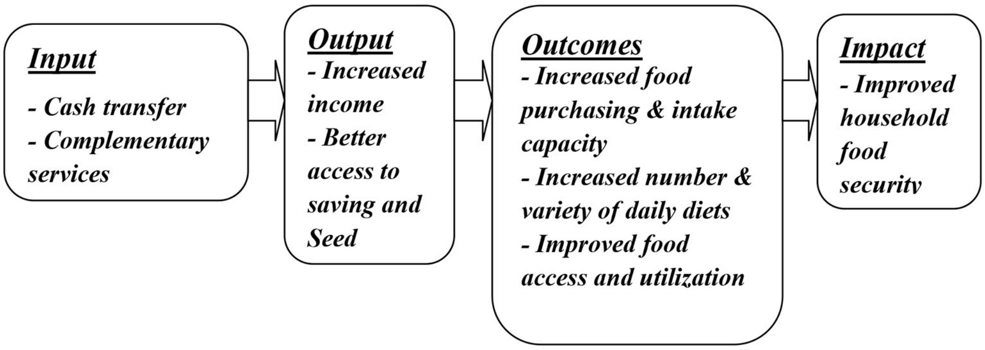

FIGURE 1
Conceptual framework; causal pathways of CTs to improve household food security. Author's adaptation from Rebecca et al. (2013).

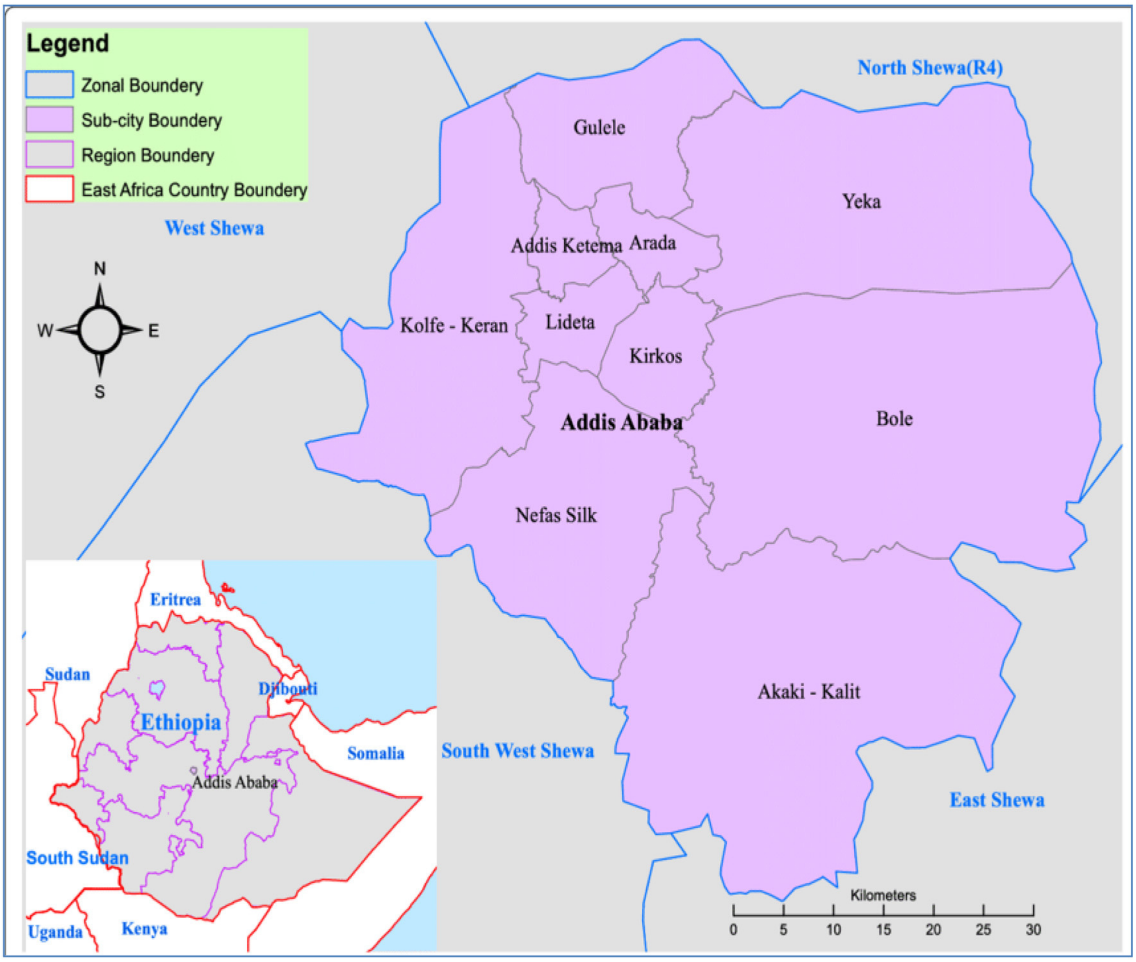

FIGURE 2
Map showing Addis Ababa with administrative sub-cities designations. Bole and Yeka sub-cities were selected randomly as sites for analysis (Ethiopian Mapping Agency, 2019).

and the limitation posed by research funding, two sub-cities, i.e., Bole and Yeka, were identified using the simple random technique. In the third stage, a sample of food-insecure program beneficiary and non-beneficiary woredas (districts) were selected in proportion to the overall number of chronically food-insecure woredas within the selected two sub-cities using simple random sampling. A total of 27 woredas (Bole-14 and Yeka-13) were reviewed to ensure a geographical dispersion of the sample and to cover a variety of representative conditions such as inner and outer-city neighborhoods in each sub-city. Finally, 8 out of 27 woredas (about 30%) were randomly chosen as representative samples of the study sites.

These eight woredas were chosen with probability proportional to size (PPS) based on the estimated chronically food insecure population (that is, the beneficiaries) of the Bole and Yeka sub-cities. From Yeka, four beneficiary woredas (namely, woreda 7, 10, 12, and 13), and from Bole, another four beneficiary woredas (namely woreda 4, 9, 10, and 15) were proportionally drawn as the study sites.

From both sub-cities, a sample size of 324 beneficiary households (HHs) was estimated using about 4,064 study population, a 95% confidence level, and the formula of Anthony (2014). So, a total adjusted sample size of 280 beneficiary households from both sub-cities or about 35 from each woreda was estimated for households with CTs group or treatment group.

From each woreda, other households (equivalently food insecure, poor but not included in the program, or households without CTs) were used for comparison with program beneficiaries through a quasi-experiment. To this end, the author selected a comparable number of eligible households living in the same woreda and equivalently food insecure and poor but currently non-beneficiary households. About 35 such households, equivalently food insecure met the selection criteria of PSNP but currently not participating in the program due to various reasons, were chosen from each woreda (or 280 from both sub-cities).

According to the discussion with local authorities, experts, households, and beneficiary selection committee, the major reasons for a restricted coverage of PSNP in the capital city were limited quota of beneficiaries needed by the program from each woreda, selection bias by the committee, lack of formal residence ID card, and non-appearance of eligible households during election time. However, they assured that for both types of households the income, food insecurity, poverty and asset levels, indicators of social networks, and exposure to economic shocks in the 2 years before the start of PSNP were similar. It was hard to gather information and test the selected outcome variables regarding both types of households such as income from before the start of PSNP due to the absence of similar surveys and past data. Therefore, having non-beneficiary households from the same communities as CT beneficiaries helped to ease the risks of PSNP impact estimation bias by providing a similar distribution of those unobserved community characteristics.

Respondent households from each woreda of both sub-cities were equally classified into two groups representing current PSNP beneficiary households with CTs (treatment group) and non-beneficiary households without CTs (control group) for quasi-experiment, and comparative and differential impact evaluation using "with and without CTs" scenario.

Households who were currently participating in the program were considered beneficiaries and included in the treatment group if they received any CTs since 2017 for undertaking work on PSNP-supported public works every month, or they had received access to at least one intervention or service provided under the CTs. Whereas households that had or had not been previous PSNP beneficiaries, who meet the selection criteria such as residence location, poverty, and food insecurity level but were not currently participating in the program were included in the comparison or control group. Other things and variables being constant, these two groups of households were made different based on the receipt (or not) of CTs to make reasonable comparisons and estimates of impacts.

Finally, specific enumeration areas (EAs) where the PSNP was active were identified within woredas using PPS sampling and in collaboration with local authorities and experts. For the household and field surveys, 280 CT beneficiary households and 280 non-beneficiary households were selected for the sample using simple random sampling with replacement using separate lists of PSNP beneficiary and non-beneficiary households. This yielded a total sample of 560 households for the quantitative household survey and quasi-experiment of this study. Samples of the PSNP survey were designed to comprise a fitting comparison group. The samples were drawn exclusively from woredas or sites where PSNP was actively operating in and about one-third of the sample was composed of non-beneficiary households living in similar neighborhoods and communities as program beneficiaries. An additional 20 key resource persons from households, experts, and managers were also purposively chosen and participated in the interviews and discussions. Thus, the sampling design, research sites, and households were assumed to be representative and provided reliable estimates, conclusions, and generalizations about the program's impacts on income and food security goals.

Mixed research and impact evaluation approaches

A mixed research approach was an ideal technique to conduct this research and provide empirical and more conclusive evidence using various approaches than a single research approach would. Considering the research questions which required both quantitative and qualitative evidence, a sequential strategy of a mixed approach was specifically suitable to obtain different but complementary data on the topic and best understand the impacts on income and food security.

The integration of quantitative and qualitative data in the form of a mixed-methods study has great potential to strengthen the rigor and enrich the analysis and findings of the CT program's impact evaluation. As studies of food security with different approaches come to different conclusions about 'who is poor' and different causation conceptions reach different conclusions about the causal impact of development programs such as CTs, a mixed research approach is used for this study. A mixed approach is an appropriate method to explore reliable knowledge and "hard" evidence based on the knowledge claim of the pragmatism research paradigm.

This mixed methods approach integrates participatory qualitative approaches and co-produces quantitative data collection tools, which provide generalizable data geared toward supporting the refinement programs to strengthen food security. These co-produced and mixed approaches could offer unique insight, complementing and enhancing existing knowledge or evidence about multidimensional issues. It could also help the researcher to complement existing data by enhancing contextualized and locally specific information about the unique urban CTs program impacts.

As both qualitative and quantitative approaches highly rely on a facilitation process, the mixed methodology is helpful to conduct a series of processes within the stages of household food security such as contextualization, community perception, household survey, verification, replication, and engagement. In line with the research questions, a mixed approach was used to integrate different data collection processes including literature review, expert consultation, semi-structured interviews, and household surveys.

Moreover, this study was done based on key elements of Engel's law and theory of change (ToC) that could be used as evidence and a basis for economic impact evaluation. Since a single source of evidence could not be used for comparative evaluation, the evidence was drawn from different methodologies. Much of the evidence came from econometric studies, case studies, and models, particularly Ex-post, Diff-in-diff, and Pre/post impact evaluation using multiple impact indicators and were used to make impact analysis.

Accordingly, this study used comprehensive impact evaluation methodologies and models that could bring new and adequate evidence to economic intervention choices such as safety net programs. The impact evaluation approach brought new evidence to urban safety net program implementation choices. It could test basic assumptions about the effects of the urban PSNP, particularly CTs, on household food security through access and availability of food. It could also test new ways of doing safety net program interventions better and shed light on the role of complementary interventions. The evidence could represent the percentage change and impact across time and targeted beneficiary households based on impact indicators such as monthly income, savings, seed money, household food purchasing, and daily food intake capacity.

Pre-post and difference-in-difference comparative assessment

A pre-post analysis approach was used based on before-after comparisons that assume that all changes over time are due to the safety net intervention measures mainly CTs, and no other factor. This temporal comparison and impact evaluation methodology were predominantly based on before and after-safety net analyses.

According to few studies (Klatt and Taylor-Powell, 2005; Heath et al., 2020), this type of pre/post analysis model, specifically a retrospective pretest evaluation design, is better for such situations that include measuring change over a very short period of time, capturing factual or routine information, attempting to gauge perceptions of change as a result of program participation, trying to diminish response-shift bias, or trying to evaluate change without having collected baseline data before the start of the program (Howard, 1980; Sudman et al., 1996).

The impacts of cash transfers of the public works sub-program were compared with a scenario that would have existed had this project not been undertaken. To this end, a "before-after" evaluation design and temporal comparison techniques were applied using pre- and post-CTs scenarios (i.e., before and after 2017). Since the urban safety net program through CTs started in 2017 in Ethiopia, this year was used as a reference point for program impact evaluation and temporal comparison. In addition to the basic elements of the theory of change and Engel's law, changes and impacts on household food consumption and security were measured using multi-criteria evaluation including the adequacy of CTs, monthly income, saving, food purchasing, intake capacities, and access to food. To account for changes and differences in beneficiary households when comparing pre and post-program income and food expenditures, the income and food security outcome variables were expressed on a per capita basis for each household. In this pre/post design, data are time variant because they are about the income and food security status of beneficiary households before and after receipt of CTs. To this end, data were collected in mid-2020 using a questionnaire survey for both the pre- and post-PSNP outcome variables.

Difference-in-difference (Diff-in-Diff or DID) and "with-without" evaluation designs or techniques were used for the analysis of impacts and differential impacts among comparable groups based on with and without the beneficiary status of poor households. For this purpose, two groups were designed as balance tests between poor households who were recipients and non-recipients of CTs. These analysis techniques could help to determine which group of poor households benefited more from food consumption and security through CTs.

Accordingly, a quasi-experiment, particularly propensity score matching (PSM) was used. The researcher used these statistical techniques to construct an artificial control group by matching each treated unit (i.e., treatment group of program beneficiaries) with a non-treated unit (i.e., comparative group of non-beneficiaries) of similar characteristics and variables except the receipt of CTs. Using these matches, the researcher could estimate the impact of CTs. It was conducted between program beneficiary households with CTs and non-beneficiary poor households without CTs (as a control group). This statistical technique was employed by studying the differential effect of CTs as a treatment or intervention on a 'treatment group' vs. a "control group" to highlight the differential impacts of CT on income and food security.

As indicated in the sampling technique section, 280 households receiving CTs were identified for the treatment group and another 280 households who were not receiving CTs were identified for the control group. Although the control group differs in the absence of treatment (i.e., CTs) both groups were strongly believed to be comparable, identical, or equivalently poor households, and other variables were controlled or kept constant. As this difference in the absence of treatment in the control group was considered for the post-CT period or since 2017, it could be differenced out by deducting group-specific means of the outcome of interest, relative to the treatment group that was receiving CTs. The remaining difference between these group-specific differences must then reflect the causal effect of interest such as effects on or changes in monthly income and food purchasing power.

Description of the dataset

The primary data used in this paper were collected using district-level household surveys and semi-structured interviews as part of a larger mixed-method of explanatory research type to examine the impacts of CTs of the safety net program on income and household food security.

A cross-sectional research design was applied to collect primary data regarding the income, saving practice, food purchasing capacity, number and variety of daily diets, level of access to food, and availability of food in both pre- and post-CTs periods i.e., before and after the introduction of the program in 2017.

After data cleaning and preparation, out of 560 samples, the final and valid sample size was 541 households (beneficiary-271 and non-beneficiary-270), which resulted in a 96.6% of response rate. A review of relevant literature and documents was also carried out to find pertinent secondary data.

Data analysis methods

The impacts of CTs on food security were analyzed using both quantitative and qualitative analysis methods. As indicated in the conceptual framework section, the parameters and measures of food security that apply to developing counties are the level of monthly income, monthly food purchasing capacity, food access, and utilization, as well as food intake capacity, which is measured in terms of the number and variety of daily diets consumed before and after CTs. The impacts of other external variables such as inflation were considered and controlled.

Independent-samples *t*-test was employed to compare the mean monthly income difference between CT beneficiary households and non-beneficiary households as well as women headed households vs. men headed households. To analyze mean monthly income differences between before and after CTs on the same program beneficiary households paired samples *T*-test was used. Besides, linear regression was employed to assess the existence of a significant relationship and predict the effect of CTs on the monthly income of beneficiaries. Accordingly, this model could estimate the percentage amount of variance or change in the monthly income of beneficiaries that is explained or predicted by monthly CTs. Binary logistic regression was also run to predict the progress of female and male-headed households either to food security (or insecurity) status as a result of financial transfers and income enhancement, keeping other external factors constant.

Independent samples Mann-Whitney U and Kruskal-Wallis test were used to compare and test the existence of significant median differences in the satisfaction and agreement level of women vs. men for enhanced monthly food expenditure capacity as a result of CTs. Both were also used to test the significance of the statistical difference between CT beneficiary households and non-beneficiary households on the current average number of daily food intake in their family.

To compare and test the existence of significant median differences in the saving practice of CT beneficiary households before and after participating in PSNP, the related samples McNemar Test was employed. These statistical tests help to measure the overall impacts and progress of CTs of PSNP on household food consumption and security.

Besides, interviews and discussions were transcribed, and thematic analysis was performed including coding of qualitative data before identifying and reviewing key themes. Each theme was analyzed to find an understanding of participants' opinions and insights regarding the contributions of the CT program to the income and food security of urban poor households.

Results

The findings of this study are subject to two caveats. As data were collected more than 1 year after the program began in 2017, this study should be considered an interim assessment of the program's impact. Due to a lack of well-organized past data or surveys in the pre-CT period, the data regarding the characteristics of beneficiary households or situations before the start of the CT program was based on the memory of respondents collected through recall but not directly tested. To properly consider and address the shortcomings, the study made a special effort to ensure the inclusion of poor beneficiary and non-beneficiary households (HHs) from different sub-cities of the city with and without evaluation design.

Since the pre/post model through a retrospective pre-test evaluation design provides more information than a post-test-only design, this model was selected for its advantages of multiple data points. As indicated by various research (Howard, 1980; Sudman et al., 1996; Klatt and Taylor-Powell, 2005; Heath et al., 2020), to overcome the measurement error through response-shift bias or recall data, a meaningful pre/post-CT program comparison was done by helping participants to use the same frame of reference to measure themselves against (i.e., 2 years before and after 2017 in this study).

Besides, the author attempted to capture factual information or routine behaviors (e.g., income and food recall) and changes over a very short period of time (2 years only) that are more accurately reported in pre-tests because people remember fewer details as time passes.

The significance of effects of CTs on monthly income

Monthly income of beneficiary households before and after-CTs

After the adequacy and targeting accuracy of CTs were assessed through preliminary analysis, the real impacts, contribution, and progress of the monthly CTs on household income and food security were analyzed using various variables, indicators, and scenarios.

In Table 1, a paired samples *t*-test indicates that the mean difference between the monthly income of beneficiary households before and after cash transfer has statistical significance. The null hypothesis (H_O) stating that the monthly income of program beneficiaries before and after CTs are equal, was not accepted ($p < 0.001$). On average, participants showed a mean monthly income before CTs that was lower than the mean monthly income after CTs by about 983.33 ETB (or about 22 USD, ($p < 0.001$), two-tailed).

Here, it is imperative to bear in mind that monthly income throughout this survey refers to the overall income of households including the cash transfer provided by the Public Works Program and other additional income from various direct or indirect sources.

Regarding the total monthly income of households participating in PSNP vs. non-participating households in Table 2, both Levene's test and independent samples *t*-test indicate that the null hypothesis which states that the average monthly incomes of both households participating and not participating in PSNP is equal was rejected at ($p < 0.001$).

The mean difference between the average monthly income of participating and non-participating households in PSNP was statistically significant. On average, participants showed that the mean monthly income of households participating in PSNP or program beneficiaries was higher than the mean monthly income of non-beneficiaries or non-participating households by about 1,089.5 ETB (or about 24 USD, ($p < 0.001$), two-tailed).

How do CTs affect and predict income of HHs participating in PSNP

As indicated in Table 3, linear regression was calculated to predict the monthly income of program beneficiaries based on monthly cash transfers in ETB ($p < 0.001$). The null hypothesis which stated that the coefficient is equal to zero i.e., the monthly CTs has no relationship and no effect on the monthly income of beneficiaries was rejected.

Thus, a significant regression equation was found ($p < 0.001$). From the Pearson correlation model, it was found that monthly CTs was positively and strongly correlated with monthly income ($p < 0.001$). Besides, a model summary shows that 55.8% of the variance or change in monthly income is explained and predicted by CTs.

The regression model evidence also shows that when monthly CTs provided to an individual program beneficiary increased by 1 ETB (or about 0.0224 USD), the monthly income also increased by 1.57 ETB (or about 0.0351 USD).

According to the interviews with key resource persons on the effects and contribution of this safety net program, one major reason for its recognition was that the safety net program, mainly the public works sub-program, directly addressed shortages of income and vulnerability. Subsequently, the effects and benefits of this program were evaluated to be immediate, positive, and indirect, by addressing income inequalities and making economic growth more inclusive among the poor.

Monthly food cost of beneficiaries before and after taking part in PSNP

A paired samples *t*-test in Table 4 indicated that the mean difference between the monthly food cost or expenditure of beneficiaries before and after participating in PSNP had statistical significance. The null hypothesis was not accepted ($p < 0.001$). On average, participants showed that the mean monthly food cost before-PSNP benefit was lower than the monthly food cost after-PSNP benefit by about 194.17 ETB (or about 5 USD, ($p < 0.001$), two-tailed).

Saving practice of beneficiary households before and after PSNP

In Table 5, related samples McNemar test shows that the null hypothesis (H_O) suggesting the practice of saving by beneficiaries

TABLE 1 Monthly income of beneficiaries before vs. after-CTs (in ETB).

Paired samples *t*-test							
	Paired differences				t	df	Sig.
	Mean	Std. error mean	95% Confidence interval of the difference				
			Lower	Upper			
Average monthly income before PSNP cash transfer - Average monthly income after PSNP cash transfer	−983.33	26.68	−1,035.85	−930.80	−36.85	269	0.000

Computed using survey data (2021). N:B 1ETB is equivalent to about 0.0224USD, June 2021.

TABLE 2 Monthly income of households participating in PSNP vs. non-participating households.

Independent samples *t*-test								
Levene's test for equality of variances				*T*-test for equality of means				
		F	Sig.	t	Sig.	Mean difference	95% Confidence interval of the difference	
							Lower	Upper
The monthly average income of respondents in ETB	Equal variances assumed	102.2	0.000	30.7	0.000	1,089.5	1,019	1,159
	Equal variances not assumed			30.8	0.000	1,089.5	1,020	1,158

Computed using survey data (2021). N:B 1ETB is equivalent to about 0.0224USD, June 2021.

is equally present both before and after the start of PSNP, is rejected ($p < 0.001$). Besides, in the cross-tabulation analysis shown in Supplementary material, it was found that about 213 replied "YES" and only one respondent and "NO" to the question "Do you practice saving from monthly income after the start of PSNP?". Similarly, about 213 replied "NO" and only one respondent replied "YES" to the question "Do you practice saving from monthly income before the start of PSNP?". Thus, the monthly saving practice of beneficiaries was not present in the period before participating in PSNP, whereas it was present in the post-PSNP period.

Level of food purchasing power of households participating in PSNP vs. non-participating households

In Figure 3, Mann-Whitney U and Kruskal-Wallis tests show that there was a statistically significant difference in food purchasing power, at Pearson chi-square ($p < 0.001$). The food purchasing power of households participating in PSNP was greater than households who were not participating in PSNP.

The food purchasing power of 35.7, 29.4, 16.4, 6.7, 5.2, 4.5, and 2.2% of 269 households participating in PSNP were High, Very High, Extremely High, Neutral, Low, Very Low, and Extremely Low, respectively. Conversely, the food purchasing power of 35.8, 27.4, 26.3, 6.6, 1.5, 1.5, and 1.1% of 274 non-participating households were Very Low, Low, Extremely Low, Neutral, Very High, Extremely High, and High, respectively.

Significance of PSNP to female beneficiaries compared to their counterparts

To promote the differential impact analysis on the impact and contribution of PSNP cash transfers from a gender perspective, the program's significance, particularly to female-headed households was compared to male-headed households. This survey reviewed the gendered-impacts of the programs and how outcomes differed according to the gender of program beneficiaries.

TABLE 3 How does financial transfer affect and predict income of households: Linear regression model.

Correlations

Correlation	Variables	Income (in ETB)	Cash transfer (in ETB)
Pearson correlation	Income (in ETB)	1.000	0.747
	Cash transfer (in ETB)	0.747	1.000
Sig.	Income (in ETB)	.	0.000
	Cash transfer (in ETB)	0.000	.
N	Income (in ETB)	269	269
	Cash transfer (in ETB)	269	269

ANOVA[a]

Model		Sum of squares	df	Mean square	F	Sig.
1	Regression	37053921.810	1	37053921.810	336.687	0.000[b]
	Residual	29384535.430	267	110054.440		
	Total	66438457.250	268			

Model summary[b]

Model	R	R square	Adjusted R square	Sig. F change
1	0.747[a]	0.558	0.556	0.000

Coefficients[a]

Model		Unstandardized coefficients		t	Sig.	95% Confidence interval for B	
		B	Std. error			Lower bound	Upper bound
1	(Constant)	519.52	66.68	7.79	0.000	388.22	650.82
	Cash transfer (in ETB)	1.57	0.08	18.34	0.000	1.41	1.74

[a]Dependent Variable: Monthly average income of respondents (in ETB). [b]Predictors: (Constant), Cash transfer received per month (in ETB). N:B 1ETB is equivalent to about 0.0224USD, June 2021. Computed using survey data (2021).

TABLE 4 Monthly food cost of beneficiaries before and after participating in PSNP.

Dependent samples *t*-test

	Paired differences				t	df	Sig.
	Mean	Std. error mean	95% confidence interval of the difference				
			Lower	Upper			
Average food cost before participating in PSNP-Average food cost after participating in PSNP (in ETB)	−194.1	6.29	−206.56	−181.78	30.86	265	0.000

Computed using survey data (2021).

TABLE 5 The level of saving practice of beneficiaries before and after participating in PSNP.

Related samples mcnemar test

Null hypothesis	Test	Sig.	Decision
The distribution of different values across Do you practice saving from monthly income before participating in PSNP? and Do you practice saving from monthly income after participating in PSNP? are equally likely.	Related Samples McNemar Test	0.000	Reject the null hypothesis

Asymptotic significances are displayed. The significance level is 0.05. Computed using survey data (2021).

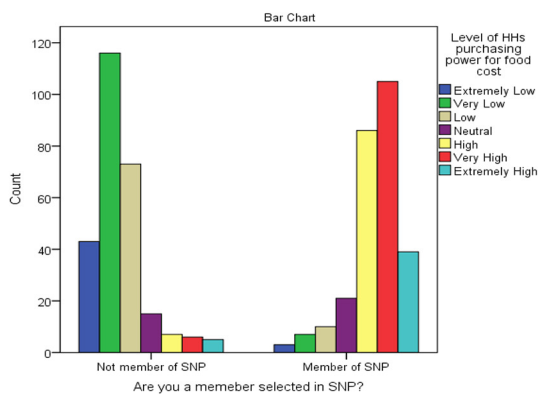

FIGURE 3
Level of the purchasing power of households participating in PSNP vs. non-participating households for food cost. Computed using survey data (2021).

Proportion of cash transfer going to female beneficiaries compared to male

In Table 6, the independent samples *t*-test indicates that the null hypothesis suggesting average monthly cash transfers going to both female and male households participating in PSNP is equal was not rejected ($p < 0.056$). The mean difference between monthly cash transfers going to female and male households participating in PSNP was not statistically significant. On average, participants showed that the mean monthly cash transfer received by female and male program beneficiaries was 767.75 (or 17 USD) and 712.72 ETB (or 15.9 USD) respectively.

The mean monthly cash transfer difference between female and male program beneficiaries was only 55 ETB (or 1.2 USD, ($p < 0.056$), two-tailed). As one of the key dimensions of gender-based analysis was assessing whether cash transfers were targeted to female or male, and whether there was a significant difference between both recipients. This study found that female program beneficiaries were receiving an equally good amount of cash transfer or benefit as male beneficiaries per month.

Monthly income of female beneficiaries compared to male beneficiaries

In Table 7, the independent samples *t*-test indicates that the null hypothesis stating that the average monthly income of both female and male households participating in PSNP is equal was rejected ($p < 0.035$). The mean difference between the monthly income of female and male households participating in PSNP was statistically significant. On average, participants showed that the mean monthly income of female and male beneficiaries was 1,760.48 (or 39.4 USD) and 1,635.26 ETB (or 36.6 USD) respectively. The mean monthly income difference between female and male beneficiary households was 125 ETB (or 2.8 USD, ($p < 0.035$), two-tailed). Thus, it was found that in the post-PSNP period monthly income of women CT beneficiary households was higher than the income of their men counterparts by about 125 ETB. Here, monthly income refers to the overall income of households from various direct and indirect sources including the cash transfer.

Agreement level of female beneficiaries compared to male about PSNP outcomes on the food expenditure capacity

As indicated in Figure 4, independent samples of the Mann-Whitney *U* test and the Kruskal-Wallis test were also run to check the significance of the difference in the level of agreement between female and male beneficiaries toward positive outcomes of PSNP on their food purchasing capacity. Thus, the null hypothesis which indicates that the level of agreement on positive outcomes of PSNP is the same across categories of sex was rejected, ($p < 0.001$). Regarding the outcomes of PSNP on food purchasing capacity, the level of agreement of female and male beneficiaries had a statistically significant difference.

Figure 4 also shows that the majority or 59.1 and 29.6% of 115 female beneficiaries agreed and mostly agreed, respectively, on the positive benefits of PSNP toward food purchasing capacity. On the other hand, out of 151 male beneficiaries, 60.9 and 30.5% agreed and mostly agreed respectively. Similarly, binary logistic regressions also showed that female beneficiary HHs have more possibility to achieve food security status than

TABLE 6 The proportion of CTs received by female vs. male program beneficiaries.

		Levene's test for equality of variances		*T*-test for equality of means				
		F	Sig.	t	Sig.	Mean difference	Lower	Upper
How much cash transfer is received per month (in ETB)?	Equal variances assumed	0.026	0.872	1.92	0.056	55.03	−1.38	111.4
	Equal variances not assumed			1.92	0.055	55.03	−1.18	111.2

Computed using survey data (2021).

TABLE 7 Monthly income of female beneficiaries vs. male beneficiaries: Independent samples *t*-test.

		Levene's test for equality of variances		*T*-test for equality of means				
		F	Sig.	t	Sig.	Mean difference	Lower	Upper
Monthly income of respondents in ETB	Equal variances assumed	7.68	0.006	2.08	0.038	125.22	6.93	243.52
	Equal variances not assumed			2.12	0.035	125.22	9.08	241.36

Computed using survey data (2021).

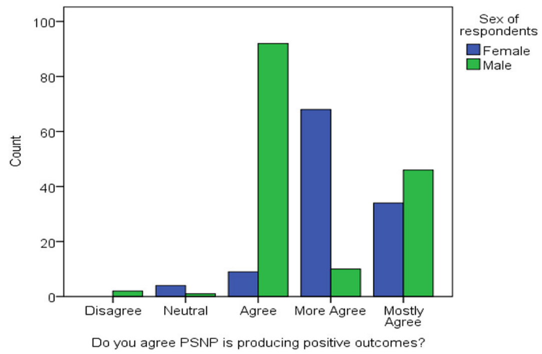

FIGURE 4
Agreement level of female beneficiaries compared to male toward positive outcomes produced by PSNP on food purchasing capacity. Computed using survey data (2021).

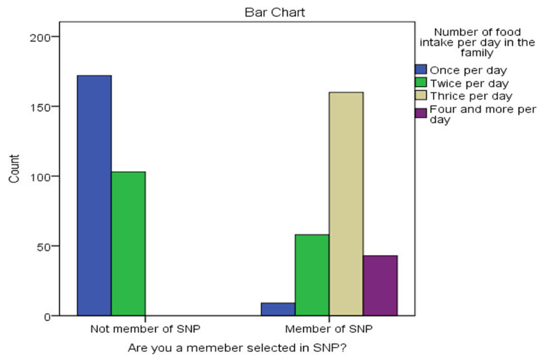

FIGURE 5
The existing number/frequency of daily food intake between program beneficiary households and non-beneficiary households. Computed using survey data (2021).

male HHs as a result of the financial transfers and enhancements of income. That meant the possibility of going to the status of food insecurity was more for male beneficiary households than female ones.

Number of daily food intake of beneficiary vs. non-beneficiary households

Independent samples Mann Whitney U and Kruskal-Wallis tests were run to test the statistically significant difference between program beneficiary households and non-beneficiary households in the number of daily food intake in families. Figure 5 shows that there was a significant difference between program beneficiary and non-beneficiary households in the average number or frequency of daily food intake in the family (Pearson Chi-Square, $p < 0.001$).

Figure 5 demonstrates that among the households which are not beneficiaries of PSNP, 62.5 and 37.5% currently take food one and two times per day on average, respectively. Whereas among the households who are beneficiaries of PSNP, 3.3, 21.5, 59.3, and 15.9% currently take food one, two, three, and more times per day on average, respectively.

The existing numbers or frequency of daily food intake at the family level in households who are not beneficiaries of this safety net program are by far lower than those households who are beneficiaries of the safety net program.

Shortcomings and challenges of PSNP implementation

This section seeks to address the key research question "What factors affect the implementation, contribution, and impacts of safety net program on sustainable income and livelihood of the poor?" Based on the survey, interviews of key resource persons, and evidence, the following findings regarding limitations and challenging factors that negatively affect the implementation of PSNP and its effects were found.

- The majority of beneficiaries receive cash/financial transfer and inputs for public works activities such as uniform clothes, shoes, work equipment, gloves, and safety materials, but not always on time,
- For the majority of households, their cash transfer was characterized by a reducing trend in the past two to three years in comparison to the current cost of living, local market, and periods of shock such as the novel coronavirus (COVID-19) pandemic,
- The inclusion of some non-eligible beneficiaries as well as the distribution of benefits that are not adequately targeted at the poorest quintile groups of program beneficiaries,
- Lack of supply-side supplementary services and support by concerned bodies, and
- Lack of awareness and cooperation from the community residing around public work areas.

Discussions

The results of the impacts and progress of the urban safety net CT program on income, food expenditure, and intake capacity of the urban poor are discussed as follows.

The significance of effects of the CT program

Monthly income of beneficiaries in the post-CT period relative to both pre-CT periods and non-beneficiaries

Few studies (Bourguignon et al., 2004; Arnold and Conway, 2011) indicate that by improving the income of households in the short term and human capabilities in the long term, and cash assistance given by public work sub-program to poor households may increase the affordability of food, health care, or education. Recent research has also found that CTs significantly increases expenditures for both male and female recipients, in comparison to non-recipients (Blattman et al., 2013; Green et al., 2015).

To measure the real effects and progress of the program through this survey, one of the basic outcome variables - monthly household income of program beneficiaries in the post-CT period - was compared with their income before the start of the program and against the income of non-beneficiary households. This study found that the monthly income of beneficiary households in the post-CT period had increased by about 983.33 ETB (or 22 USD) compared to monthly income in the pre-CT period mainly because of the financial support provided by the public works sub-program. This meant that the financial assistance provided by the program could make a change of about a 140% increase in the monthly income of beneficiary households.

Besides, evidence showed that there was a significantly different impact across program beneficiary and non-beneficiary households on household income. Overall current monthly income was substantially higher for program beneficiaries receiving a cash transfer compared to the monthly income of poor households not benefitting from the program. This meant the existing monthly income of poor households who are not participating in the program was far lower because they were not selected by the program to receive a financial benefit. By considering an equivalent poverty level between both groups of households, it was found that the monthly income difference of 1,089.5 ETB (or 24 USD), i.e., over 100 percent, is because of the financial benefits going to poor households participating in the program.

This evidence generally reveals that the largest share in the increase of total income of program beneficiary households in the last couple of years is linked and attributed to financial benefits provided by the public works sub-program. This financial assistance going to poor households is making a significant change in the improvement of their monthly income. Thus, it is easy to understand that as planned this public work sub-program is showing positive impacts and progress on the income of the poor by significantly increasing the size of monthly income. The enhancement of household income, in turn, has its implication and contribution to better seed money, household food expenditure, consumption, and access.

How do CTs affect and predict income of beneficiary households

Gilligan and Sarah (Gilligan, 2013; Sarah, 2013) confirmed that financial benefits provided to poor households and individuals have wide-ranging outcomes such as better income, savings, and expenditure. Additionally, recent studies (Arnold and Conway, 2011; Honorati et al., 2015) indicate that financial assistance going to poor households from the public work sub-program may increase the affordability and intake of food, health, or education by enhancing their monthly income in the short term and human capabilities in the long term. As an outcome of CTs, consistent household income may improve and stabilize food consumption over time (Maxwell et al., 2013; Rebecca et al., 2013).

Correspondingly, based on evidence obtained from the linear regression analysis of this study it can be suggested that monthly cash transfer is a good predictor variable for monthly income. This is because the regression coefficient shows that for every additional ETB in financial transfer, income is expected to increase by 1.57 ETB (or 0.0351 USD) on average. If the monthly financial transfer is zero, monthly income is expected to remain at 519.52 ETB (or 11.6 USD) on average. Accordingly, in the post-PSNP financial transfer period, more than 50% of the increase in the monthly income of program beneficiaries is due to financial transfer.

This evidence demonstrates that a significant share in the increase of income of beneficiary households in the last 2 to 3 years can be attributed to financial benefits provided by the public works sub-program. Thus, it is possible to infer that the implementation of PSNP is showing significant progress and effect on the advancement of income and food in poor households.

Monthly food cost of beneficiaries before and after taking part in PSNP

In addition to Engel's law and change theory, few other studies (Gilligan et al., 2008; Bastagli et al., 2019) reveal that there is a comparatively large evidence base connecting financial or cash transfers to an increase in household total expenditure including expenses on food, housing, and poverty reductions. An increase in total household expenditure is associated with all kinds of financial benefits such as an increase in per capita monthly total expenditure and a 15% increase in total monthly consumption expenditure for urban households (Haddad et al., 2015; Pega et al., 2015; Mohammadi, 2016).

It is shown that the range of increase from a 5.3 percentage point change in total percapita expenditure to a 33 percentage point change in total expenditure respectively (Braido et al., 2012; Perova and Vakis, 2012; Baye et al., 2014).

CTs increases not only household income and food purchasing capacity but also households' access, availability, and utilization of food which are the basic requirements for improved household food security (Anna, 2013).

Household food expenditure capacity was considered as an outcome variable and performance indicator to evaluate the real impact and changes brought about by the cash transfer program. Accordingly, the current food expenditure capacity status of beneficiary households (in the post-financial transfer period) was compared to their status before 2017 (pre-financial transfer scenario).

Similarly, evidence about the impact of cash transfers on food expenditure shows that the mean monthly food expenditure capacity of beneficiary households had comparatively increased in the post-financial benefit period. It increased from 273.87 ETB or about 6.1 USD (mean monthly food cost pre-PSNP benefit scenario) to 468.05 ETB or about 11 USD (post-PSNP benefit scenario); the increase was about 194.17 ETB (approximately 5 USD). This meant the monthly food expenditure capacity of households showed a 59% (on average) increase mainly because of the financial benefit provided by the program.

Considering the generally increasing nature of food costs in Addis Ababa from time to time, the largest share in an increase of food expenditure capacity in the last couple of years post-2017 can be attributed to benefits provided by the program.

Therefore, it is possible to conclude that the urban safety net through its financial assistance has provided positive outcomes as planned. Financial assistance to poor households has made a significant change and improvement in their food expenditure capacity. It has produced significant contributions to the enhancement of food expenditure of poor households by increasing their monthly income. This positive outcome in turn implies the improvement of household food expenditures, intake, access, and food security status.

Saving practice of beneficiaries before and after taking part in PSNP

Concerning the impacts of cash or financial transfers on saving practice, the findings of several studies mostly showed statistically significant positive effects. For example, recent studies (HLPE, 2012; Haushofer and Shapiro, 2013) found that doubled cash savings balances and a 10% increase in the share of households saving has an effect of getting financial benefit from Kenya's Give Directly program. In Mexico, financial benefits or cash transfers resulted in a significant increase in the likelihood of having savings as well as access to a bank account and credit for beneficiary households, but no effects on the amounts of savings (Gertler et al., 2006; Angelucci et al., 2012).

Financial transfers provided by the SAGE program in Uganda resulted in a statistically significant increase in the proportion of beneficiary households that have savings (Merttens et al., 2015).

In this study, the current status of saving practices of beneficiaries (in the post-cash transfer period) was analyzed and compared to previous years' status (pre-cash transfer scenario).

Similar to other studies, this study's findings show that there is a statistically significant difference between the saving practice of beneficiary households before and after participation in the public works sub-program. Before participating and receiving financial benefits from the safety net program, the observed households had no saving practices. Whereas, in the post-PSNP period, these households developed monthly saving practices as a result of the enhancement of their monthly income through financial benefits. Evidence shows that cash transfers to poor households is making a significant positive difference in their habit or practice of saving. Getting an adequate income source can help poor households lift saving constraints and accumulate capital to start a business.

Accordingly, it is possible to understand that this safety net program is showing good progress and a range of positive effects such as increased households' saving habits and engagement with savings groups as compared to a situation in pre-financial transfer periods. Households could either use the financial benefit to increase their access to savings and credit or pay off existing debt. Such saving practices can allow poor households to satisfy future household demands, accumulate seed money, and open businesses as well as act in response to emergencies such as food insecurity, accidents, and sickness.

Level of food expenditure capacity of households participating in PSNP vs. non-participating households in PSNP

Although financial supports were underutilized, they have wide-ranging outcomes mainly on the economic and social conditions of poor households and individuals such as better household expenditure or consumption capacities when measured and compared to food aid (Adato and Bassett, 2009; Mohammadi et al., 2011). Recent research has showed that financial assistance improves socio-economic outcomes and makes food more affordable by enhancing household income in the short term and human capabilities in the medium and long term (Bourguignon et al., 2004; Arnold and Conway, 2011).

In this study, the level of monthly food expenditure power was analyzed and compared between program-beneficiary households and non-beneficiary households. The findings of this study prove that even if the poverty level of both categories of households is equivalent, their current food expenditure capacity level is significantly different. Evidence also shows that as a result of financial benefits provided by PSNP the level of food expenditure capacity of households participating in PSNP is generally higher compared to households not participating in PSNP.

The lower level of food purchasing power of the poor households who are not participating in PSNP is because they are not receiving financial transfers or benefits from the program. Among the various sources of purchasing power, financial transfer provided by PSNP accounts for the largest share or percentage for the majority of households participating in the program. Whereas, for poor households not participating in the program the dominant sources of purchasing power are beggary and help from kith and kin.

Thus, it is possible to infer that by enhancing the monthly income of poor households, the public works sub-program is playing significant and positive roles through its financial transfer. Consequently, these financial benefits provided by safety net programs could make a difference and help poor households in enhancing their food expenditure capacity as well as better food access and security.

Significance of PSNP on female beneficiaries compared to male

To promote and supplement the evaluation of the effect and progress on income and livelihood of program beneficiaries, its significance particularly to females was analyzed in comparison to males. Thus, this survey reviewed the effects of safety net programs on gender-related results and how outcomes differed according to the gender of the program beneficiaries.

Proportion of CTs going to female beneficiaries compared to male counterparts

Research focusing on eligibility and targeting performance of safety net programs surveys (Smith and Haddad, 2002; Haushofer and Shapiro, 2013; Bastagli et al., 2019) showed that both sexes benefited in different ways and there were significant differences in the impact between the main recipients. Female-headed households received financial assistance and benefited as much as their male counterparts (Pega et al., 2015; Hagen-Zanker et al., 2017).

Eligibility criteria and beneficiary targeting mechanisms may have an important mediating effect on the effects of financial/cash transfers made by safety net programs (Yoong et al., 2012; Handa et al., 2014). Due to this reason, the actual benefits and progress of the public works sub-program toward female-headed households were further evaluated by the household survey considering an outcome variable -mainly the proportion of cash transfers going to the main recipients. Hence, the proportion of household headship and monthly cash transfer was compared between female and male beneficiary households. Since the majority of households participating in the program were female-headed, female-headed households were well-targeted by and participated in the program.

Moreover, evidence shows that the aggregate amount of financial transfers going to females was slightly higher compared to male households. Since the difference is only 55ETB and not statistically significant, it is easy to recognize that female beneficiaries received financial assistance as much as male beneficiaries. The public works sub-program is providing females with a good amount of financial assistance as males per month for the last 2 to 3 years. This has implications and contributes to reducing income inequalities between poor males and females. In general, based on evidence, it is possible to conclude that the eligibility criteria and targeting mechanisms of the public works program are gender-sensitive and inclusive as planned.

Monthly income of female beneficiaries compared to male beneficiaries

Concerning the impact of the financial transfer on the monthly income of beneficiaries of both sexes, some studies (Blattman et al., 2013, 2014; Green et al., 2015) have revealed a statistically insignificant positive effect of financial transfer for females i.e., no increase in expenditure and income for female beneficiaries compared to males. On the contrary, it was found that both sexes benefited from safety net programs in different ways and significant differences remain between the main recipients (Yoong et al., 2012; Bastagli et al., 2019).

In this study, the current monthly income of female beneficiary households were compared against male beneficiary households. Accordingly, a statistically significant difference in the monthly income of female and male beneficiary households was seen. Regardless of equivalent cash transfers received by both categories of beneficiaries in post-PSNP, the overall monthly income of female beneficiaries was found to be higher by about 125 ETB compared to their male counterparts. Even though this amount of income difference may not be substantively larger enough considering the current local market value, such differences are created when financial transfers are either spent or invested.

As per the opinion of most of the key resource persons, while financial transfers are often spent on monthly expenses by male beneficiaries, financial transfers are not only spent but also saved up and invested by female beneficiaries for additional income-generating businesses. If not the only, financial transfers for these female households are the dominant source of income which also indirectly helps them as means of seed money to take part in other supplementary income-generating activities. However, male beneficiaries are found to be relatively weaker in taking part in supplementary income-generating activities.

Since female households are relatively more vulnerable groups in the urban community, it is fair and acceptable to benefit them as well as enhance their income through such types of financial transfers. Although another detailed assessment is required to show more statistically significant differences in outcomes for both sexes, the available evidence of this study indicates that female households are not just participating in the program well but are also getting as many benefits compared to males. As planned, the public works sub-program is significantly contributing to the enhancement of income, business, food access, consumption, and security of poor women households in the city.

Agreement level of female beneficiaries compared to male about outcomes of PSNP on the food expenditure capacity

According to Yoong et al. (2012), AIR (2014), IEG (2014) when females receive financial benefits or cash transfers, consumption decisions were often found to be more focused on children and investing in different types of assets compared to males. Providing financial benefits to females makes a difference and significantly enhances female's empowerment and decision-making power independently and jointly with their husbands in urban areas.

Evidence shared in few studies (Perova and Vakis, 2012; Rebecca et al., 2013; Hagen-Zanker et al., 2017) confirm that cash transfers have positive outcomes on women's opportunities such as monthly income, household purchasing power, and reduction of child labor for program beneficiaries of both sexes. Notably, it could help to reduce the time spent on domestic work by women compared to men.

In this study impact of the CT program on female-heade households were also evaluated using the opinion of beneficiaries about their satisfaction or agreement level on actual benefits and contribution of the program to food purchasing capacity. Hence, the current level of satisfaction or agreement was compared between both sexes. Evidence shows that the overall level of agreement of female beneficiaries on the benefits of PSNP to food purchasing capacity and food security status is slightly higher than males. Although the majority of female and male beneficiaries tend to agree on the benefits of financial transfers to food purchasing capacity, male beneficiaries' level of agreement or satisfaction and food security status is relatively lower.

This means the recipient of cash transfers, whether male or female, has an impact on outcomes such as the purchasing capacity, access, and utilization of food. Cash transfers have differing impacts on female beneficiaries compared to males both directly and indirectly. Besides, the existing number or frequency of daily food intake by families of non-beneficiary households is twice and once on average. On average, most beneficiary households take food three, two, and four times per day. Because of membership in the program and financial transfers received, the existing numbers of daily food intake at the family level in beneficiary households are far greater than in non-beneficiary households.

From this, it is possible to understand that PSNP is showing good progress and significantly contributes toward the improvement of food purchasing capacity and the daily food intake of poor communities. The involvement and benefit of poor female households are given relatively better attention by PSNP. As planned, poor female-headed households are not only better covered and participated in PSNP, but they are also better benefited and satisfied by the financial benefits for the enhancement of their overall income and food security status.

Shortcomings and challenges of PSNP implementation

The implementation of the safety net and the graduation of beneficiaries are widely affected by challenges (Daidone et al., 2015; Heath et al., 2020). Although PSNP CTs of public works sub-program is significantly contributing and progressing toward the enhancement of income and food consumption, and security of households, factors are affecting the implementation and contribution of the program. Hence, the program's shortcomings and challenging factors that negatively influence the implementation and observed benefits include: first, the timing of financial transfers and provision of inputs for public works activities such as uniform clothes, work equipment, and safety materials are often delayed and postponed for an unknown time.

Second, the monthly financial transfers being provided since 2017 are reducing in their amount and lower in value as compared to the current market and cost of living. Such unintended effects and problems resulted from the rigid nature of the benefits system and are often magnified by the influences of unexpected periods of disasters such as increasing inflation and recently the state of emergency due to the novel coronavirus (COVID-19) pandemic. Third, although this program is generally pro-poor, there is the inclusion of some non-eligible beneficiaries as well as the distribution of benefits that are not adequately targeted at the poorest quintile groups of program beneficiaries.

Lastly, a lack of supply-side supplementary services and support such as training, information, supervision, and follow-ups may hinder the complete achievement of PSNP objectives and contributions. Improper waste disposal practices of local communities on public work sites, and lack of adequate awareness and cooperation from the residents' side are also constraints.

Conclusions

This study provides a household survey, impact analysis results, and evidence of how financial or cash transfers provided by urban PSNP in Addis Ababa have contributed in terms of impacts, roles, and progress toward enhancement of income and food security of poor households. In line with key assumptions of the theory of change and Engel's law regarding the changes expected from the intervention program, overall evidence reveal how powerful and influential financial transfers provided by safety net programs are. Evidence also reveal the wide-ranging changes and effects on program beneficiary households.

This study reports statistically significant results and the vast majority of cash transfers are in the progress toward the direction that policymakers intend to achieve. Because of the consistency of findings across the critical outcome areas and multiple indicators employed by this study, findings are found to be particularly significant.

Since the targets of this cash transfers program under implementation are poor and nearly poor households it is found to be pro-poor and good in targeting accuracy. Besides, the survey conducted by this study has indicated clear and significant impacts of the CTs program, especially for intended outcomes such as monthly income, savings, expenditure capacity on food, frequency of daily food intake, and access to seed money for a business.

There is stronger evidence showing that financial transfers or CTs account for a larger share of the monthly income of the vast majority of beneficiary households. Findings suggest that the financial transfers sub-program can play a key role in improving livelihoods across the region. Interestingly, the information gathered for this study strongly suggests that the post-financial transfer phase had favorable effects and modifications on savings, seed money, household food expenditure, and intake capacity.

When compared to pre-PSNP conditions and impoverished non-beneficiary households, it is observed that these outcome factors are greater for program-beneficiary households in the post-PSNP period.

Thus, cash transfers have resulted in significant incremental change and benefits including the enhancement of households' income, and access to and consumption of food. This study examines whether impacts vary amongst families based on the sex of the primary beneficiary. A bigger percentage of cash transfers going to female households provides compelling evidence of the importance of cash transfers for beneficiary households headed by women. Available evidence strongly confirm that CTs lead to income improvement and involvement in the supplementary business for women headed households. Cash transfers are not only spent but also saved up and invested by women beneficiaries for additional income, compared to men counterparts. Though both men and women beneficiaries tend to have better satisfaction and agreement on subsequent outcomes of CTs for food purchasing and intake capacity, women's levels of agreement are relatively superior.

As a result of financial transfers, the current number, and frequency of daily food intake by beneficiary households are also found to be greater than in non-beneficiary households. Hence, as expected the PSNP has been successful in improving income and related access to utilization, and use of food for poorer communities, especially women. Access to the CTs of the PSNP increased the likelihood that households carry out their own business or income-generating activities, but slightly reduced the likelihood that males entered the business or income-generating activities. Policymakers can realize that targeting the poor and female-headed households could potentially lead to greater proportionate income enhancement and improvements in productive livelihoods and food security. The study highlights the importance of the public works or CTs sub-program as one of the key components of the overall productive safety net program.

However, it investigates unintended effects and shortcomings of CTs that result from challenging factors that affect program implementation and helpful outcomes. This includes delayed CTs, the size and value of financial transfers reducing from year to year, mainly relative to the rising inflation, cost of living, and disasters like the COVID-19 pandemic.

To address program constraints, potential solutions are suggested such as policy reforms to scale up the CT program and expand its coverage. A timely payment, regular increase in the size of the monthly financial transfer, and additional emergency aid mainly to more vulnerable beneficiary households such as pregnant and mothers with more children are necessary.

This is especially true in periods of disasters such as the COVID-19 pandemic. Future research can be done at a relatively wider scope to compare the impacts of CTs on food security at both urban and rural people at a country or regional level.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

The author confirms being the sole contributor of this work and has approved it for publication.

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Conflict of interest

The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2022.1031213/full#supplementary-material

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Effect of artificial insemination in comparison to natural mating on the reproductive performance and profitability of smallholder pig production system in Indian Himalaya

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In fragile ecosystems, smallholder pig production systems provide food and nutritional security to resource-poor communities. Pigs are the main livestock raised by indigenous communities in the Himalayan region of India, but their productivity is low for several reasons. The present study aimed to study the pig herd size and to evaluate the impact of artificial insemination (AI) on profitability and sustainability in the small-holder pig production system. A total of 612 AIs were carried out in 483 sows in the farmer's field along with 114 sows that underwent natural breeding. A comparison was made between the reproductive performance of sows following AI and natural breeding. The profitability and economics of AI and natural breeding were also compared. The mean pig population varied from 4.75 to 6.42 in the study region. The farrowing rate, total born piglets (TBPs), and live born piglets (LBPs) were significantly higher ($P < 0.001$) in artificially inseminated sows compared to naturally bred sows (9.37 vs. 6.28; 8.93 vs. 5.45). Farrowing rate ($P = 0.005$), TBP, and LBP were significantly ($P < 0.001$) higher in sows inseminated by female inseminator as compared to male inseminator (81.26 vs. 71.42%; 9.65 vs. 8.80; 9.21 vs. 8.38). The insemination by uneducated farmers resulted in significantly ($P = 0.002$) lower farrowing rate, TBP ($P < 0.001$), LBP ($P < 0.001$), and AI per farrowing ($P = 0.042$). The farmers who did AI for the third time and more than three times recorded significantly ($P < 0.001$) higher farrowing rates, TBP, and LBP. The farrowing rate was significantly ($P < 0.001$) less in sows that were located more than 30 km away from the semen center (66.66 vs. 82.90%). The net return per sow was significantly higher ($P < 0.001$) in artificially inseminated sows (US$464.8 vs. US$248.11). AI resulted in an 87.33% increase in net returns per farrowing as compared to natural breeding. In conclusion, AI in smallholder pig production systems has the potential to sustainably improve the profitability as well as the food and nutritional security of resource-poor farmers.

KEYWORDS

sustainability, small-holder pig farms, artificial insemination (AI), economics, Indian Himalayan region

Introduction

Smallholder pig production system is being practiced by marginal or poor communities, particularly in Africa and Southeast Asia (Molotsi et al., 2021; Singh et al., 2021a). In this system, pigs are reared for households or local consumption only to sustain their livelihood. Besides, the pig plays a crucial role in religious and social ceremonies. Even though the production system is traditional with few inputs and low productivity, it still provides economical, nutritional, and food security (Singh and Mollier, 2016; Singh et al., 2019). In comparison with the intensive pig production system, the smallholder pig production system uses fewer resources, produces less waste, and is, therefore, more environmentally sustainable. The relatively small investment cost and the potential for value addition make this system a good alternative for small farmers (Park et al., 2017).

In India, most of the pig population (46%) is present in the seven states of the Eastern Himalayan region, where most pigs are raised in smallholder systems, in which farmers keep two to five pigs in their backyards mainly for fattening purposes (Singh et al., 2019, 2020a; Sharma et al., 2020). In this system, reproductive efficiency and productivity are generally low which can mainly be attributed to inbreeding (Kadirvel et al., 2013; Sharma et al., 2020; Singh et al., 2020a). For this reason, a breeding boar is used for 4–5 years for natural breeding (Kadirvel et al., 2013; Sharma et al., 2020). Also, boars used in natural mating may have a low libido score which is often overlooked by farmers. Moreover, genetics, general health condition, and flooring in mating areas are critical parameters that influence the libido of boars and subsequently their fertility (Hodel et al., 2021). In the last two decades, the pig population has seen a negative growth rate in the region (Singh et al., 2021b). Furthermore, poor farmers in this region face severe economic hardship due to the occurrence of transboundary diseases. In addition, the demand for pork is increasing due to the growing human population, increasing income, and industrialization. Therefore, urgent interventions are needed to improve pig production in a sustainable way. This can be achieved through the use of improved technology in key areas such as genetics, nutrition, management, cleanliness, and reproduction. Among these areas, artificial insemination (AI) is one of the most effective approaches to improve pig productivity (Celestin et al., 2019; Singh and Mollier, 2020). Throughout the globe, AI in pigs has improved pig fertility and reproductive efficiency with a minimum risk of diseases (Knox, 2016; Singh et al., 2021a). In Europe and North America, more than 90% of pigs are being bred with AI, while in India, less than 1% of pigs are being inseminated artificially (Knox, 2016; Singh and Mollier, 2020). The use of AI to improve smallholder pig production systems in rural areas was suggested earlier (Am-in et al., 2010; Visalvethaya et al., 2011; Kadirvel et al., 2013).

Despite the known benefits of AI, it has not percolated to the smallholder pig production system in the Eastern Himalayan region of India. There are no comprehensive reports available on how AI works in smallholder pig production systems in this region in relation to various factors affecting its performance. Therefore, the objectives of the present study were (i) to compare the reproductive efficiency of natural breeding and AI, (ii) to evaluate various factors affecting the success of AI, and (iii) to compare the profitability of natural breeding and AI in the Eastern Himalayan region.

Materials and methods

Study area

The study site is located in Nagaland (93°20°E and 95°15°E longitude and between 25°6°N and 27°4°N latitude), a state in the Eastern Himalayan region of India (Figure 1). Topographically, the state is 70% hilly regions and 30% plains regions. The climate of the region is subtropical with high humidity during the monsoon season. Annual rainfall varies from 1,500 to 2,000 mm. The temperature humidity index of the region exceeds 90 during the summer and monsoon seasons (Singh et al., 2022). For this study, the farmers were selected from three districts (Dimapur, Kohima, and Peren) of Nagaland. These districts were selected for the study due to the nearby presence of a boar semen station of the ICAR Research Complex

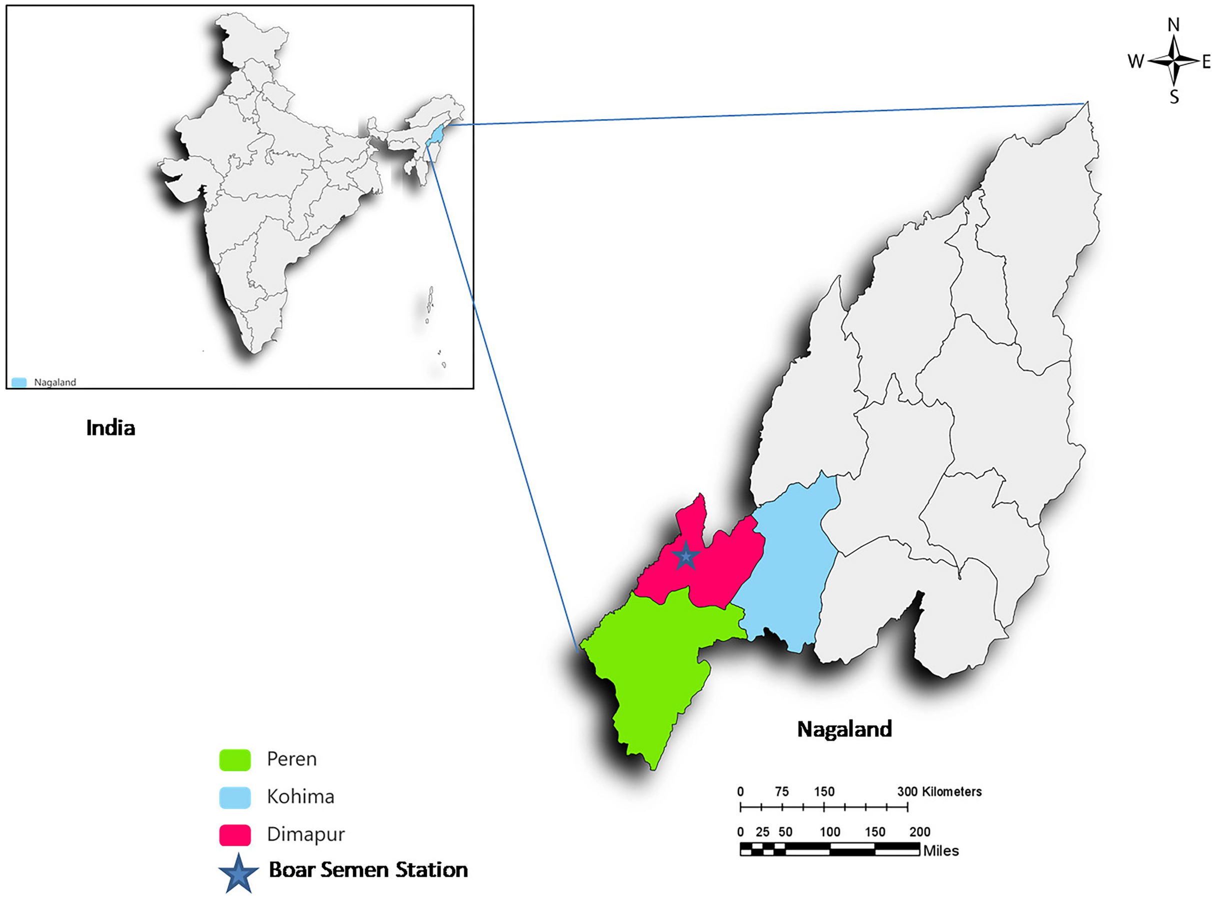

FIGURE 1
Map of the study location.

for NEH Region, Nagaland Center. Kohima is a hilly district, whereas Dimapur and Peren lie in the plain regions. These districts have the highest pig populations in the state.

Farmers' selection and sample size calculation

To collect the data, farmers from the database of the ICAR Nagaland Center were randomly selected, contacted by telephone, and then visited in the field after 1 month of AI. After AI or natural breeding, sows were observed until farrowing, and data were recorded on farrowing rate and litter size. The sample size was calculated as follows:

$$Margin\ of\ error\ (ME) = z\sqrt{\frac{\hat{p}\,(1-\hat{p})}{n}}$$

Where

$$ME = 0.05$$
$$z = 1.96\ at\ 95\%\ confidence\ interval$$
$$\hat{p} = 0.3$$
$$n = Sample\ size\ to\ be\ found$$
$$n = \frac{\hat{p}(1-\hat{p})\,z^2}{ME^2} = \frac{0.3 \times 0.7 \times 1.96 \times 1.96}{0.05 \times 0.05} = 322.7$$

So the adequate sample size will be 323.

For this study, 412 smallholder pig farms were selected and their pig herd size was recorded. Similarly, for AI, data from 612 AIs performed in 483 sows in the farmer's field during 2019 and 2020 were collected. A total of 452 and 160 AIs were performed by the farmers and research associates (veterinarians), respectively, using a Golden Gilt (IMV, France) catheter. Data from 114 naturally bred sows were also collected from the smallholder pig breeders for comparison with AI.

Semen collection and processing

The semen doses used in the present study were collected from boars (Ghungroo × Hampshire) reared at the ICAR Nagaland Centre's Pig Research Farm. Semen from boars was collected using the gloved hand method (Singh and Mollier, 2020). Semen was transported in a thermos flask to the laboratory within 15 min of collection. The semen quality parameters were evaluated in the laboratory. The ejaculates with more than 70% total motility and <20% abnormal spermatozoa were selected for use in the AI program. After examination of the semen (both macroscopically and microscopically), it was diluted in PRIMXcell (IMV, France) extender. The dilution was done in such a way that each insemination dose (80 ml) contained 3 billion motile spermatozoa. The processed liquid boar semen was stored at 17°C in biochemical oxygen demand (BOD) incubator. Semen was transported to the sites of AI in temperature-conditioned thermos boxes on the day of insemination.

Artificial insemination and natural breeding

Artificial insemination in pigs is being promoted in this region through the Do It Yourself model under the Mega Seed Project on Pigs funded by the Indian Council of Agricultural Research. In this model, farmers collect the AI kit (extended liquid boar semen and AI catheter) from the boar semen station at ICAR Nagaland Center and perform AI themselves. Training on AI is regularly provided by the Center to pig breeders, but anyone who wants to inseminate pigs can purchase the kit. Estrus was detected by behavioral signs such as swelling and reddening of the vulva, vulvar discharge, vocalization, in-appetence, boar-seeking behavior, ear popping, and standing for back pressure. The procedure of AI is performed in a neat and clean environment (pig pen) by taking into consideration all the sanitary measures including cleaning the vulva to remove urine and feces and use of a new AI catheter. For AI, the tip of the catheter is lubricated with a non-spermicidal gel and inserted into the vagina for passage into the cervix while rotating anti-clockwise. After locking the catheter in the cervix, the semen pouch is attached to the catheter and the semen is allowed to flow into the cervix using gravity and gentle pressure over a 3- to 4-min period. The catheter is inserted at an angle of 30° to the backbone (Singh and Mollier, 2020). After the complete deposition of the semen, a catheter is gently withdrawn by simultaneously twisting it in a clockwise direction. During insemination, the female pig was stimulated by rubbing the flank and underlying region; however, boar and boar taint spray were not used for simulation. When bred naturally, sows were served by the rental or hired boar. Sows were of second to fifth parity and were Hampshire and Ghungroo crossbred. A grouping of farmers was also done according to experience: first timers (who did AI for the first time), second timers (who did AI for the second time), third timers (who did AI for the third time), and more than three times (who did AI more than three times). Training includes no training, group training (3 days residential), and individual training (1–2 days) on AI for farmers. The farrowing rate was calculated as the proportion of artificially inseminated or naturally bred females that farrowed. In addition, AI per farrowing, total piglets born/litter (TPB), live-born piglets/litter (LBPs), number of weaned piglets (WPs), stillborn piglets (SBPs; piglets that are born dead at farrowing)/litter, and mummies (mummified fetuses are due to autolysis and dehydration, without maceration, and born with the litter)/litter was also recorded. In the households studied, one to two breeding sows were raised in backyard production systems and piglets were sold at the age of 2–3 months.

Comparison of the economics of artificial insemination and natural breeding

For economic analysis, the cost and return of the breeding system only are included as other production costs were similar in both systems. For natural breeding, transportation cost includes transportation of sow to boar farm. For AI, transportation cost includes transportation of the AI kit from the semen station to a pig farm. The cost of natural breeding is the amount charged by the owner of the boar for breeding. For AI, the breeding cost per sow includes the cost of two AI kits (two extended semen pouches and catheters) as supplied by the boar semen station at ICAR Nagaland Center.

Statistical analysis

All statistical analyses were performed using SPSS version 27 (IBM). Data were examined for normality by the Shapiro–Wilk test. The farrowing rate was compared using Pearson's χ^2 test. One-way ANOVA was performed to study the effect of different factors on the reproductive performance variables. The differences between means were determined by Duncan's *post-hoc* test. Quantitative variables were summarized as mean ± standard error of mean (SEM). Pearson's correlation coefficient (r) was computed to see the strength and significance of the relationship among variables (Table 1). Differences were considered statistically significant at a 95% confidence level ($P < 0.05$).

The monetary expenditure incurred for natural breeding and AI was summed up and expressed as the total cost of production. Gross returns were the summation of total economic gain from natural breeding and AI. The economic

TABLE 1 Correlation table of different factors affecting the success of artificial insemination in smallholder pig production system.

	AI by	Gender	Education	Age	Experience	Training	Semen storage time	Distance	FR
AI by	1								
Gender	0.33	1							
Education	−0.25	−0.10	1						
Age	0.64	0.16	−0.33	1					
Experience	−0.30	−0.04	0.43	−0.29	1				
Training	−0.41	−0.15	−0.04	−0.13	0.02	1			
Semen storage time	−0.01	−0.11	−0.10	0.10	−0.25	0.12	1		
Distance	0.00	0.04	0.14	0.04	0.03	0.05	0.05	1	
FR	−0.02	0.11	0.15	−0.16	0.28	0.16	−0.16	−0.19	1

AI by, AI done by research associate or farmers; FR, farrowing rate; Distance, distance of pig farm from the semen station.

TABLE 2 Pig population structure in the smallholder pig production system in Indian Himalaya (mean ± SD).

	Dimapur ($n = 158$)	Kohima ($n = 147$)	Peren ($n = 107$)	*P*-value
Sows	1.44 ± 0.58^{a}	1.40 ± 0.70^{a}	1.12 ± 0.18^{b}	0.040
Boars	0.06 ± 0.24	0.03 ± 0.18	0.03 ± 0.20	0.072
Castrated boars	1.89 ± 0.89^{a}	1.42 ± 0.78^{b}	1.40 ± 0.68^{b}	0.042
Growers	1.23 ± 0.66	1.54 ± 1.18	1.22 ± 0.98	0.21
Piglets	1.80 ± 0.34^{a}	1.32 ± 0.78^{b}	0.98 ± 0.94^{c}	0.016

Means with different superscripts in a row differ significantly ($P < 0.05$).

expenses and gain have been changed to US dollars (US$) for better understanding and readability. The following economic indices were measured.

Net Return (US$ farrowing − 1) = Gross return (US$ farrowing − 1) − Production cost (US$ farrowing − 1).

Benefit : Cost ratio : Gross return (US$ farrowing − 1)/ cost of production (US$ farrowing − 1).

Results

Pig population in smallholder pig production system in the studied region

The pig population structure in the studied region is presented in Table 2. In all three districts, the castrated boar population was numerically higher than other categories of pigs. The number of sows was significantly higher ($P = 0.040$) in Dimapur (1.44) and Kohima (1.40) districts as compared to Peren (1.12) district. The number of castrated boars was significantly higher ($P = 0.042$) in the Dimapur district (1.89 vs.1.42). Similarly, the number of piglets was significantly higher ($P = 0.016$) in Dimapur (1.80 vs.1.32).

Effects of type of breeding and inseminator on reproductive performance of pigs in smallholder pig production system

The effect of breeding methods and inseminator on the reproductive performance of the sow is presented in Table 3. The farrowing rate was significantly higher ($P < 0.001$) in artificially inseminated sows (77.78%) compared to naturally bred sows (60.52%) (Figure 2). Similarly, TBP, LBP, and WP were significantly higher ($P < 0.001$) in artificially inseminated sows (9.37 vs. 6.28; 8.93 vs. 5.45; 8.33 vs. 5.06). Stillborn piglets were higher ($P = 0.015$) in naturally bred sows (0.75 vs. 0.33). The number of breeding per farrowing was significantly higher ($P < 0.035$) in naturally bred sows (2 vs. 1.71). No effect of inseminator on farrowing rate, SBP, mummified fetuses, and the number of breeding per farrowing was observed. However, TBP and LBP were significantly higher ($P < 0.05$) in sows inseminated by research associates (9.77 vs. 9.23; 9.38 vs. 8.77). Weaned piglets (8.93 vs. 8.12) were significantly ($P < 0.001$) higher in sows inseminated by research associates.

Effects of gender, age, education, experience, and training of farmers on reproductive performance of pigs in smallholder pig production system

The farrowing rate was significantly ($P = 0.005$; $r = 0.11$) higher in sows inseminated by female inseminators (81.26%)

TABLE 3 Effect of breeding methods and inseminator on reproductive performance of sows in smallholder pig production system.

	Numbers of animals inseminated (*n*)	Number of breedings	Farrowing rate (%)	TBP	LBP	WP	SBP	Mummified
Breeding methods								
AI	612	1.71 ± 0.02^b	77.78^a	9.37 ± 0.08^a	8.93 ± 0.08^a	8.33 ± 0.06^a	0.33 ± 0.03^b	0.06 ± 0.01^a
Natural breeding	114	2.00 ± 0.00^a	60.52^b	6.28 ± 0.09^b	5.45 ± 0.07^b	5.06 ± 0.05^b	0.75 ± 0.05^a	0.06 ± 0.01^a
P-value		0.035	<0.001	<0.001	<0.001	<0.001	0.015	0.68
AI done by								
Research associates	160	1.66 ± 0.04^a	79.37^a	9.77 ± 0.14^a	9.38 ± 0.12^a	8.93 ± 0.08^a	0.29 ± 0.05^a	0.09 ± 0.02^a
Farmers	452	1.73 ± 0.02^a	77.21^a	9.23 ± 0.10^b	8.77 ± 0.10^b	8.12 ± 0.08^b	0.35 ± 0.03^a	0.06 ± 0.01^a
P-value		0.086	0.571	0.019	0.004	<0.001	0.37	0.27

Means with different superscripts in a column differ significantly ($P < 0.05$). TBP, total born piglets; LBP, live born piglets; WP, weaned piglets; SBP, stillborn piglets.

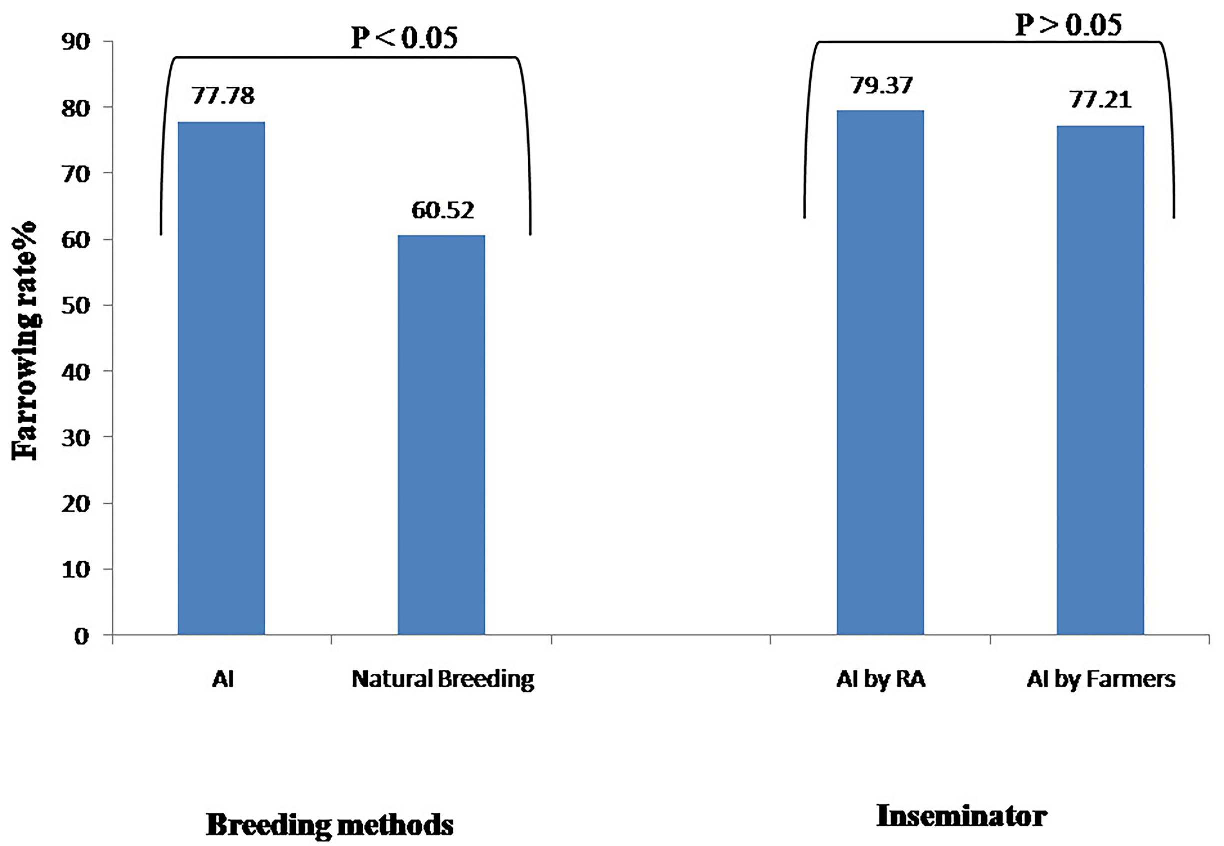

FIGURE 2
Effect of breeding methods and inseminators on the farrowing rate of pigs in smallholder pig production system.

compared to male inseminators (71.42%) (Table 4). Similarly, TBP and LBP were significantly ($P < 0.001$; $r = 0.11$) higher in sows inseminated by female inseminators (9.65 vs. 8.80; 9.21 vs. 8.38). Farmer's age had a significant effect on reproductive outcome, with younger inseminators (25–40 and 41–50 years) recorded significantly ($P < 0.001$; $r = -0.16$) higher farrowing rate (85.10 vs. 55.79%), TBP (9.60 vs. 8.25), and LBP (9.17 vs. 7.90) compared to older inseminator. Uneducated farmers recorded significantly ($P = 0.002$; $r = 0.15$) lower farrowing rate (64.15%), TBP (8.32) ($P < 0.001$), LBP (7.94) ($P < 0.001$), and AI per farrowing (1.66) ($P = 0.042$). The farmers who did AI for the third time and more than three times recorded significantly

TABLE 4 Factors affecting the success of AI in smallholder pig production system in Indian Himalaya.

	Numbers of animals inseminated (n)	AI per farrowing	Farrowing rate (%)	TBP	LBP	SBP	Mummified
Gender of farmers							
Male	217	1.70 ± 0.03^{a}	71.42^{b} (155)	8.80 ± 0.13^{b}	8.38 ± 0.12^{b}	0.32 ± 0.04^{a}	0.09 ± 0.02^{a}
Female	395	1.71 ± 0.02^{a}	81.26^{a} (321)	9.65 ± 0.11^{a}	9.21 ± 0.10^{a}	0.34 ± 0.03^{a}	0.05 ± 0.01^{a}
P-value		0.823	0.005	<0.001	<0.001	0.743	0.160
Age of farmers							
25–40 years	282	1.68 ± 0.03^{a}	85.10^{a} (240)	9.60 ± 0.11^{a}	9.17 ± 0.11^{a}	0.31 ± 0.04^{a}	0.07 ± 0.01^{a}
41–50 years	192	1.76 ± 0.03^{a}	82.81^{a} (159)	9.58 ± 0.16^{a}	9.09 ± 0.14^{a}	0.39 ± 0.05^{a}	0.08 ± 0.02^{a}
51–60 years	138	1.72 ± 0.05^{a}	55.79^{b} (77)	8.25 ± 0.21^{b}	7.90 ± 0.21^{b}	028 ± 0.06^{a}	0.03 ± 0.02^{a}
P-value		0.654	<0.001	<0.001	<0.001	0.542	0.141
Education							
Uneducated	106	1.66 ± 0.05^{b}	64.15^{b} (68)	8.32 ± 0.23^{b}	7.94 ± 0.21^{b}	0.33 ± 0.08^{a}	0.04 ± 0.03^{a}
Elementary	188	1.72 ± 0.03^{a}	81.91^{a} (154)	9.49 ± 0.16^{a}	8.98 ± 0.16^{a}	0.37 ± 0.06^{a}	0.05 ± 0.02^{a}
High school	131	1.80 ± 0.03^{a}	79.38^{a} (104)	9.49 ± 0.20^{a}	9.04 ± 0.18^{a}	0.34 ± 0.05^{a}	0.08 ± 0.02^{a}
Above high school	187	1.67 ± 0.03^{b}	80.21^{a} (150)	9.66 ± 0.13^{a}	9.27 ± 0.11^{a}	0.30 ± 0.04^{a}	0.09 ± 0.02^{a}
P-value		0.042	0.002	<0.001	<0.001	0.467	0.138
Experience							
First timer	135	1.64 ± 0.05^{b}	56.29^{c} (76)	8.38 ± 0.23^{b}	7.94 ± 0.24^{b}	0.26 ± 0.03^{a}	0.05 ± 0.03^{a}
Second times	125	1.73 ± 0.04^{ab}	80.00^{b} (100)	8.93 ± 0.17^{b}	8.49 ± 0.17^{b}	0.36 ± 0.08^{a}	0.06 ± 0.02^{a}
Third times	97	1.79 ± 0.04^{a}	90.72^{a} (88)	9.73 ± 0.21^{a}	9.27 ± 0.19^{a}	0.39 ± 0.07^{a}	0.05 ± 0.02^{a}
More than three times	255	1.70 ± 0.03^{ab}	83.13^{ab} (212)	9.80 ± 0.12^{a}	9.37 ± 0.10^{a}	0.33 ± 0.04^{a}	0.08 ± 0.02^{a}
P-value		0.035	<0.001	<0.001	<0.001	0.681	0.254
Training							
No training	153	1.68 ± 0.05^{a}	53.59^{b} (82)	8.04 ± 0.20^{b}	7.64 ± 0.17^{b}	0.34 ± 0.06^{a}	0.04 ± 0.02^{a}
Group training	197	1.73 ± 0.03^{a}	87.30^{a} (172)	9.63 ± 0.14^{a}	9.23 ± 0.14^{a}	0.35 ± 0.05^{a}	0.05 ± 0.01^{a}
Individual training	262	1.71 ± 0.03^{a}	84.73^{a} (222)	9.67 ± 0.12^{a}	9.19 ± 0.11^{a}	0.32 ± 0.04^{a}	0.09 ± 0.02^{a}
P-value		0.602	<0.001	<0.001	<0.001	0.487	0.175

Means with different superscripts in a column differ significantly ($P < 0.05$). TBP, total born piglets; LBP, live born piglets; SBP, stillborn piglets.

($P < 0.001$; $r = 0.28$) higher farrowing rates (83.13%), TBP (9.80), and LBP (9.37) as compared to first and second timers. AI per farrowing was significantly ($P = 0.35$) less when AI was done by a first-timer (1.64 vs. 1.79).

Effect of semen storage duration and distance of AI center on reproductive performance of pigs in smallholder pig production system

The effect of semen storage time and distance of AI center on the reproductive performance of sows after AI are presented in Table 5. Semen storage beyond 48 h significantly reduced ($P < 0.001$; $r = -0.16$) the farrowing rate (67.51 vs. 85.65%), TBP (8.97 vs. 9.57) ($P = 0.041$), and LBP (8.57 vs. 9.14) ($P = 0.038$) compared to other two groups. The farrowing rate was significantly ($P < 0.001$; $r = -0.19$) lower in sows that were located more than 30 km away from the semen center (66.66 vs. 82.90%).

Comparison of cost-benefit analysis of natural breeding vs. artificial insemination of pigs in smallholder pig production system

A cost-benefit analysis of natural breeding vs. AI is presented in Table 6. The total breeding cost was significantly ($P < 0.001$) lower in artificially inseminated sows (US$5.64 vs. US$37.64). Net return per sow was significantly ($P <$

TABLE 5 Effect of semen storage time and distance of AI center on reproductive performance (mean ± SEM) of sows in smallholder pig production system.

	Numbers of animals inseminated (*n*)	AI per farrowing	Farrowing rate (%)	TBP	LBP	SBP	Mummified
Semen storage time							
<24 h	171	1.65 ± 0.04[a]	78.94[a] (135)	9.51 ± 0.16[a]	9.14 ± 0.15[a]	0.29 ± 0.04 [a]	0.05 ± 0.02[a]
24–48 h	244	1.74 ± 0.03[a]	85.65[a] (207)	9.57 ± 0.13[a]	9.05 ± 0.12[a]	0.37 ± 0.04[a]	0.08 ± 0.02[a]
48–72 h	197	1.72 ± 0.03[a]	67.51[b] (133)	8.97 ± 0.17[b]	8.57 ± 0.16[b]	0.31 ± 0.06[a]	0.06 ± 0.02[a]
P-value		0.67	<0.001	0.041	0.038	0.25	0.87
Distance from the semen center							
<10 km	193	1.73 ± 0.03[a]	82.90[a] (160)	9.16 ± 0.16[a]	8.89 ± 0.15[a]	0.31 ± 0.04[a]	0.06 ± 0.02[a]
10–30 km	263	1.72 ± 0.03[a]	80.60[a] (212)	9.58 ± 0.13[a]	9.08 ± 0.12[a]	0.35 ± 0.04[a]	0.07 ± 0.02[a]
>30 km	156	1.67 ± 0.04[a]	66.66[b] (104)	9.45 ± 0.16[a]	9.02 ± 0.15[a]	0.34 ± 0.06[a]	0.06 ± 0.02[a]
P-value		0.71	<0.001	0.053	0.11	0.29	0.83

Means with different superscripts in a column differ significantly ($P < 0.05$). TBP, total born piglets; LBP, live born piglets; SBP, stillborn piglets.

TABLE 6 Cost-benefit analysis of natural breeding vs. artificial insemination per farrowing in smallholder pig production system (value in USD*).

Variables	Natural breeding ($n = 114$)	Artificial insemination ($n = 612$)	*P*-value
Cost			
Transport cost	6.27[a] (transportation of sow or boar)	1.88[b] (transportation of AI kit)	<0.001
Breeding cost per sow	31.37[a]	3.76[b]	<0.001
Total cost	37.64[a]	5.64[b]	<0.001
Benefits			
Sale of piglets@USD56.74 per piglets	285.76[b] (5.06 average piglets weaned per farrowing)	470.44a (8.33 average piglets weaned per farrowing)	<0.001
Net return per farrowing	248.11[b]	464.8[a]	<0.001
Percent increase in net return in AI per farrowing		87.33%	
B:C ratio	7.59	83.41	<0.001

Means with different superscripts in a row differ significantly ($P < 0.001$). *One USD = INR 79.68.

0.001) higher in artificially inseminated sows (US$464.8 vs. US$248.11). AI resulted in an 87.33% increase in net returns per farrowing.

Discussion

In the study region, the pig population in each household varied from 2 to 8 in number which is in agreement with previous studies (Kadirvel et al., 2013; Mbuza et al., 2016). The smallholder pig production system is constrained by economic resources and, therefore, has few pigs. The present study showed that the productivity and profitability of the smallholder pig production system increased significantly after the adoption of AI, as measured by more weaned piglets and higher net returns. In this study, the reproductive efficiency in terms of farrowing rate, TBP, and LBP was much better in artificially inseminated sows as compared to naturally bred sows. Similarly, the number of breeding per farrowing was less in AI-bred sows. This is consistent with previous studies (Am-in et al., 2010; Visalvethaya et al., 2011); however, another study (Kadirvel et al., 2013) found no difference in farrowing rates between AI and naturally bred sows. The improved reproductive efficiency in AI-bred sows may be attributed to the selection of superior boars and the laboratory examination of the semen quality (Visalvethaya et al., 2011). The health status (Hodel et al., 2021) and frequency of use of rental boars may compromise semen quality, which would potentially reduce their reproductive efficiency (Am-in et al., 2010). It was previously reported that farmers uses the same boar for breeding purpose in a village for three to four years over few breedable sows (Kadirvel et al., 2013; Singh and Mollier, 2020). This leads to inbreeding which results in low productivity and reproductive efficiency. It was earlier reported that an increase in pig inbreeding is greater in populations with smaller effective population sizes (Lopes et al., 2019). Our previous studies on organized farms have reported similar reproductive performance in pigs bred by AI in subtropical climates (Singh et al., 2020b, 2021a, 2022).

In the present study, AI by research associates and farmers yielded similar farrowing rates, however, TBP and LBP were higher in sows inseminated by research associates. This is because research associates are veterinarians, exposed to technology, and better trained than farmers. The management of AI is very important to determine the success of the procedure and the reproductive performance of the sows (Maes et al., 2011). Visalvethaya et al. (2011) reported no difference between AI done by technicians and farmers. This might be due to differences in the skill levels of farmers. Visalvethaya et al. (2011) selected the trained farmers only, whereas, in the present study, farmers were randomly selected regardless of their previous exposure to AI technology.

It was noted that female inseminators were much more successful in AI compared to male inseminators in terms of farrowing rate, TBP, and LBP. This is in contrast to previous reports (Visalvethaya et al., 2011; Mbuza et al., 2016; Celestin et al., 2019), reporting better performance by male inseminators. In the study area, women mainly look after livestock and pig farming (Singh et al., 2020b). It has been previously reported that technology adoption depends primarily on access to resources and information rather than gender (Doss and Morris, 2001). In addition, age, education, experience, and training of farmers affected the performance of AI in this study. In terms of experience, the performance of first-timer and second-timer inseminators was lower as compared to the third-timers and beyond. It was previously reported that farmers with higher education and more experience in AI tended to perform more efficiently (Visalvethaya et al., 2011; Celestin et al., 2019). Young and educated farmers are eager to learn new farming technologies and are much more receptive to the technologies. Training the farmers individually or in groups increased the success of AI. Farmer's inexperience can lead to improper storage, transportation, thawing, and insemination of semen. In the AI of pigs, heat detection and correct AI procedure are the critical steps for a successful outcome (Singh and Mollier, 2020). Visalvethaya et al. (2011) observed that farmers with no training experience observed more backflow of semen during AI processes which affected the success of AI. Training and experience tend to improve correct insemination timing and AI procedure. Sharma et al. (2020) documented that a lack of training and exposure to AI technology are the major impediments to the successful adoption of AI in pigs.

In the present study, boar semen stored beyond 48 h negatively affected the reproductive efficiency of AI. It is well known that boar sperms are prone to oxidative stress during liquid storage because of their unique membrane composition (Aitken and Drevet, 2020; Singh et al., 2021a). Singh et al. (2021a, 2022) reported that a high THI index in the subtropical region negatively affected the boar semen quality which was subsequently reflected in the poor reproductive efficiency of AI. Haugana et al. (2005) reported that increasing the semen storage time in the BTS extender from 4–14 to 52–62 h reduced piglets' litter size by 0.5. The reduced success of AI with aged semen may be because of decreased sperm motility and livability which reduced their fertility. Contrary to our findings, Visalvethaya et al. (2011) did not find any difference in reproductive performance because of semen storage time and methods of semen transportation. The difference could be because of breed, extender, and training exposure to the inseminators. Furthermore, the farmers located within 30 km of the semen center reported better success with AI as compared to those located more than 30 km away. Similar to our findings, Celestin et al. (2019) reported that the success of AI in pigs decreased with an increase in the distance between the semen center and the pig farm. This is possible that with an increase in the distance between the farm and the semen center, semen transportation and semen storage conditions will affect the outcome of AI. However, Am-in et al. (2010) revealed that distance to the AI center did not affect the farrowing rate and non-return to oestrus. The difference could be due to breed, semen extender, semen storage condition, trained inseminator, or climate.

In terms of profitability and income enhancement, the net return per farrowing was much higher in artificially inseminated sows. By adopting AI, farmers saved the expenditure involved in the maintenance of breeding boar. Kadirvel et al. (2013) also reported higher profitability by doing AI in backyard pig production systems. In addition to the direct increase in profitability, AI leads to access to the best genetics, increased genetic gain, improved reproductive efficiency, and enhanced boar use efficiency (Knox, 2016; Niyiragira et al., 2018; Singh and Mollier, 2020). Increased pig productivity can indirectly impact the food and nutrition security of smallholder pig producers by increasing food spending, income diversification, and ecological resilience.

Conclusion

The findings of the present study have important policy implications for the promotion of AI in the smallholder pig production system in the Indian Himalayan region. This study has demonstrated that AI improved the productivity and profitability of this food production system. There was a marked increase in profitability with the adoption of AI in this production system. In the long-term, this intervention may improve ecological resilience as a result of decreased dependence on wildlife and natural resources in this fragile ecosystem. The success of this model will help the resource-poor farmers to increase their nutritional and economic security on a sustainable basis. In nutshell, AI in smallholder pig production systems is recommended to enhance the profitability and food security of resource-poor farmers.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Ethics statement

The animal study was reviewed and approved by Institute Animal Ethics Committee of ICAR Research Complex for NEH Region, Umiam, Meghalaya, India. Written informed consent was obtained from the owners for the participation of their animals in this study.

Author contributions

MS and RM: conceptualization, investigation, methodology, and data. RP and NP: investigation and data. RY and JC: data and writing—review and editing. MS, RK, and SB: writing—original draft, review, and editing. DR and VM: supervision and resources. All authors have read and approved the final manuscript.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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A study on agricultural investment along the Belt and Road

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On the basis of the theories of overseas foreign direct investment (OFDI) and New Economic Geography, the factors influencing the grain industry investment in the countries along the Belt and Road (herein after referred to as the "B&R countries") were discussed, and the impacts of such investment in terms of the bilateral economic distance, institutional environments and the farmland resource levels of host countries were analyzed in depth in this study, thus expanding the theoretical analysis framework of OFDI. Empirically, the dependence on China's overseas investment was applied to measure the bilateral economic distance, and these two variables were incorporated into the empirical model along with the location characteristics of the institutional environments of host countries. The Zero-inflated Poisson Model was applied to analyze China and the B&R countries. A conclusion derived is as follows: the farmland resources of the B&R countries have a positive impact on China's overseas farmland investment, and the location characteristics of the B&R countries vary greatly. China should confer great importance to regional comparative advantages, conduct differentiated cooperation in farmland investment, strengthen the conservation of water and land resources and safeguard of farmers' livelihoods in the less developed regions, and guarantee the grain security in developing countries, while valuing the distribution and sales of agricultural products in developed regions and greatly enhance the ties between enterprises and local markets to ensure the sustainable development of grain industry investment projects in the B&R countries.

KEYWORDS

"Belt and Road", grain industry, investment, empirical study, sustainability

Introduction

The grain crisis are signs of a rising number of hungry people worldwide and world grain price fluctuations are clear warnings that the community with a shared future for mankind is being challenged (Xia, 2019). Some countries highly value the development of scientific and technological means to increase the grain yield, yet are limited by the mismatch between economic, scientific and technological levels and the spatial distribution of water and land resources. Countries and international organizations have gradually paid wide attention to the importance of the international call for innovative approaches to collectively address and prevent grain crises (Akt et al., 2019), the valuable practice of some major economies that are starved of the resources studying the feasibility of using other countries' resources to ease their development constraints vitalizes the overseas farmland investment that optimizes global resource allocation (Brutschin and Fleig, 2018), coordinates the supply of agricultural products, and impacts the global agricultural market (Salameh and Chedid, 2020). Scholars' research on investment issues is specific to the field of foreign agricultural investment, paying more attention to foreign agricultural investment issues (Qiu et al., 2013), foreign agricultural investment strategies (Song and Zhang, 2014; Chen et al., 2015), global agricultural strategies (Cheng and Zhu, 2014; Li et al., 2016), global agricultural resource utilization (Jia et al., 2019), overseas cultivated land investment (Han et al., 2018; Jiang et al., 2018), agricultural "going global" support policies and other counter measures; As for the research on American foreign investment, it mainly focuses on investment location selection (Gao et al., 2013), influencing factors (Guo, 2017), investment experience (Thomas et al., 2017) and other fields, while there is less research on American foreign investment in agriculture, and more attention is paid to American agricultural investment strategies Board for International Food and Agricultural Development and investment effects (Jack and Ching-Wai, 2018) in developing countries from the perspective of international assistance. In China's case, the sustainable development of agriculture is being impeded by the earlier economy running system at the cost of less space for agricultural production and the ways to ensure grain supply that are detrimental to the ecological environment. The grain supply-demand conflict is being intensified between tightening resources supply and soaring demands. Overseas investment in agriculture may be a good option to ease the pressure on China's agricultural production resources and resolve the conflict between limited resources and growing demands (Li et al., 2019). As a top-level cooperation initiative at the national level, the "Belt and Road" initiative has been participated by 65 countries, including China, Mongolia, Russia, 11 countries in Southeast Asia, 8 countries in South Asia, 16 countries in West Asia and North Africa, 16 countries in Central and Eastern Europe, 5 countries in Central Asia, 6 countries in the Commonwealth of Independent States, and Italy, which signed a new memorandum in March 2019. On the whole, the cooperative countries of the "the belt and road initiative" Initiative cover almost the whole Asian continent, Eastern Europe and North Africa. From the geographical advantage, China is not far from Mongolia, Russia, five countries in Central Asia and eleven countries in Southeast Asia, and even borders with many countries, which creates certain basic conditions for China's agricultural cooperation with foreign countries. That follows the growing opportunities of cooperation between China and the B&R countries are frequent transnational exchanges and communications and cross-regional cooperation in terms of agriculture. Integrated utilization of global agricultural resources is also an effective approach to ensure grain security and end hunger and poverty in both China and the B&R countries. Improving the capability of ensuring the grain supply of the B&R countries contributes to the grain security of China. The regions along the "Belt and Road" are rich in grain resources, with a huge market for the grain trade, as the world's main production area of rice and wheat. China imports grains mainly from North America and South America. The B&R countries, such as the countries in Central Asia and Southeast Asia with great grain export potential and large grain import, enjoy obvious location advantages. On the other hand, it is necessary to increase the grain production capability in countries at risk of grain insecurity. Seventy percent of the B&R countries are low- and middle-income countries, which are expected to see the most portion of the growth in global grain demands in the years to come. From the perspective of embracing overseas investment, the global supply chain built under the Belt and Road Initiative will make a big difference in balancing the allocation of China's agricultural resources. The focus of economic cooperation of China's Belt and Road Initiative is to jointly solve the grain issue based on the grain demand of the B&R countries with the development of the "Belt and Road". This favors China's grain market reforms and overseas investment cooperation, enabling China to really get involved in the rational allocation of global grain resources and secure its grain import. Being a new model for regional cooperation and development, the "Belt and Road" seeks to maximize the role of border provinces and accelerate their regional economic integration. The China-ASEAN transport corridor meandering over Southwest China is superior to the sea corridor in terms of transport distance, time, and cost. Connecting the figure skating championships in middle and western China with neighboring Southeast Asia, South Asia, and Central Asia will facilitate joint infrastructure networking, information exchange, and other programs. Through space expansion, sustained efforts are made to advance the Belt and Road Initiative and integrative development of Northwest China by regional bilateral and multilateral trade, aiming to explore rules of market integration suited to regional cooperation, and optimize the market structures of Northwest and Southwest China. Since the farmland investment is different from general overseas foreign direct investment (OFDI), farmland investors should possess a unique competitive advantage to make overseas farmland investment and consider feasibility (whether the farmlands can be obtained *via* overseas investment) and return of such investment in the host countries. These issues have led researchers to develop a comprehensive assessment framework for the investment climate in the host countries (Deininger, 2011). For the above-mentioned analysis, the question to be addressed in this chapter is: what are the factors influencing China's overseas farmland investment in the B&R countries? Are the factors that play a decisive role in the stage of investment decision-making and the stage of scale decision-making the same? In the coming part, an econometric approach is adopted to analyze the major factors influencing China's farmland investment in the B&R countries, and identify the impact mechanism of China's overseas farmland investment, seeking to provide empirical supports for such investment behaviors. The impacts of geographical factors on China's overseas farmland investment will be specified, and then targeted policy recommendations on optimizing investment strategies, avoiding investment risks, and improving the investment level will be proposed, which is practically valuable to help promote the development of China's overseas farmland investment, ensure the stable situation of grain security and supply, and improve the competitiveness and impact of agriculture.

Literature review

There remains a large gap between China's grain supply and demand and a necessity for moderate grain import, according to China Statistical Yearbook (Wei and Li, 2019). China has switched from being a net grain exporter to a net importer since the 1990s, showing distinct regional characteristics. Despite the low proportion of the three major staples in total world trade, the import sources are western countries, led by the United States. The grain trade matters economically and politically. Other countries will impact China, a grain importer, if China fails to reasonably lessen the need for import and stand free from reliance on import (Helpman et al., 2004). In the face of the mismatch between supply and demand in the future, therefore, it is of great significance to find a way of implementing diversified import strategies and diversifying the risk of China's grain import by taking advantage of opportunities brought by the Belt and Road Initiative. The studies on China's grain import have borne some fruits. Some researchers argue that China can appropriately increase imports from the international market to regulate its domestic grain supply and demand. However, large amounts of imported grain can raise concerns about genetic safety and the safety of people's lives. The key to ensuring grain security lies in optimizing foreign trade in grain, improving grain market management, and reducing dependence on imports (Baldwin, 2003). Specifically, since the advantages of the wheat markets of Russia, Ukraine, and Kazakhstan outweigh their disadvantages, China should incorporate these countries into its expected strategic framework for global grain resource allocation to ensure its grain security (Hao and Ma, 2012). After a review of existing literature, some researchers have studied the efficiency of China's grain imports, yet failed to delve into the nationwide problem through the lens of the Belt and Road (Rauch and Trindade, 2002). Consolidating grain trade relations with the B&R countries effectively abate the shortages of farmland resources in China. Accordingly, the efficiency and trade potential of China's grain imports are discussed with exemplification of the B&R countries. Most B&R countries are developing countries, often featured by less developed economies and poor infrastructure. The destabilizing factors in some of those countries, including civil unrest, complicated geopolitics, sharp religious and cultural conflicts, backward legal system, and insecure fairness and efficiency of trade, which will take a heavy toll on the stability and sustainability of China's grain import (Wan and Lu, 2018).

Analysis on causes of location concentration of China's overseas investment

Factors of host countries

Hypothesis

> Hypothesis 1: Chinese enterprises prefer the B&R countries with a closer bilateral distance for location selection of farmland investment (higher degree of market access).

As shown in Table 1, the descending order of the agricultural trade volume between China and the B&R countries in six regions in 2017 is Southeast Asia, Northeast Asia, South Asia, West Asia and North Africa, Central and Eastern Europe, Central Asia. The trade volume has been declining with the geographical distance except for the differences among the five countries in Central Asia.

> Hypothesis 2: the scale of China's farmland investment is positively related to the favorable institutional environment in a host country.

The institutional environment is measured by the Worldwide Governance Indicators (WGI). The higher the WGI score, the better the institutional environment of a host country, and vice versa. From the point of transaction costs, there are high fixed costs of Chinese agricultural enterprises to tap the markets of the B&R countries. A stable institutional environment helps protect the private property rights and economic interests of investing enterprises while reducing the loss of profits due to corruption or legal loopholes. It is generally accepted by the academic community that the institutional environments of the B&R countries will produce complex and heterogeneous impacts on China's import and export trade. Some researchers analyzed the impacts of the Asian and European institutional environments on China's import and export trade from a regional perspective and found that the impacts of regional heterogeneity were prominent. Other researchers summarized the institutional environments of the B&R countries by degree of legal perfection, political stability, and government integrity, and concluded that the impacts on China's export trade vary with different types of institutional environments of the host countries. According to the statistics of the B&R countries and WGI released by the World Bank,

TABLE 1 Trade volume of agricultural products between China and B&R countries.

Region	Total import and export (USD 10,000)	Percentage (%)	Export amount (USD 10,000)	Import amount (USD 10,000)	Trade balance (USD 10,000)
5 countries in Central Asia	91,920.6	2	47,255.8	44,664.8	2,591.0
2 countries in Northeast Asia	452,974.2	9.9	206,489.3	246,484.9	−39,995.6
11 countries in Southeast Asia	3,198,850.9	69.7	1,584,433.4	1,614,417.5	−29,984.1
7 countries in South Asia	301,061.1	6.6	160,097.9	140,963.2	19,134.7
20 countries in West Asia and North Africa	299,025.6	6.5	248,232.9	50,792.7	197,440.2
19 countries in Central and Eastern Europe	246,132.0	5.4	88,480.7	157,651.3	−69,170.6
Total	4,589,964.4		2,334,990.0	2,254,974.4	80,015.6

Source: The Ministry of Commerce of the People's Republic of China.

the average scores of WGI of 63 B&R countries raised from −0.954 to −0.77 from 2005 to 2017, indicating a gradual improvement in the overall institutional environments in the regions. Accompanied by the progress of the "Belt and Road", China has been deepening its cooperation in grain trade with the B&R countries, striving to make the grain trade bilateral instead of unilateral export. After a comprehensive analysis and objective assessment of the systems, political landscapes, laws, and regulations of China's major trading partners, it is concluded that the unilateral export generates a limited promotion to Chinese agricultural products, even though the institutional environments of the B&R countries have been improved overall and significantly.

> Hypothesis 3: the affluence of farmland resources in host countries is positively related to the scale of China's overseas farmland investment.

Figure 1 shows development level indexes of B&R countries. Figure 2 shows spatial distribution of agricultural resource elements in B&R countries. The analysis of the Belt and Road—Information Development Index (B&R-IDI) and the number of resident-selected patent applications shows an imbalance among the B&R countries in terms of the level of scientific and technological development. The countries in Central and Eastern Europe often gained higher B&R-IDI scores than the countries in South Asia and Southeast Asia, and Afghanistan gained a low score at 14.08.

Empirical analysis of factors of host countries and location selection of China's OFDI

Selection of variables

(1) Explained variable

Since the host countries, politically sensitive to the farmland investments from other countries, may involve in backstage operation in investment projects, and the specific information on the amounts of foreign farmland investment by countries is not yet available from internationally public authoritative databases. Therefore, referring to the method of selecting dependent variables for overseas farmland investment in empirical studies by Wan and Lu (2018), the scale of farmland investment in the B&R countries was determined as a dependent variable to describe the trend of investment location selection made by Chinese enterprises and determine the trend of farmland investment in the B&R countries.

(2) Explaining variable

The farmland resource was taken as the main explaining variable in this study. The rapid growth of China's population and economy over the past 40 years has contributed to a climbing demand for grain, while putting pressure on the carrying capacity of its farmland resources, compounded by the ever-increasing demand for grain. The limited areas and uneven regional distribution of farmland make it highly geographical. The land and the freshwater resource factors, which constitute the farmland resources, would be unlikely to change much over a period, according to the results of the previous study herein. Consequently, regardless of the inconsistency between previous empirical findings on the attractiveness of natural resources for China's OFDI, the level of farmland resources in the host countries will play a part in the sustainable business development of transnational enterprises, given the long cycle of overseas farmland investment. Based on this, it is assumed that the farmland resources (res) in host countries are positively related to the scale of China's overseas farmland investment. The data of farmland resources in this study were attained by directly referring to the results of the study by Tian (2020).

(3) Control variables

Bilateral distance. In the Country-risk Rating of Overseas Investment, the relationship between the host countries and China is used as a measure of policy resistance and political friendship between the two sides. The indicator encompasses

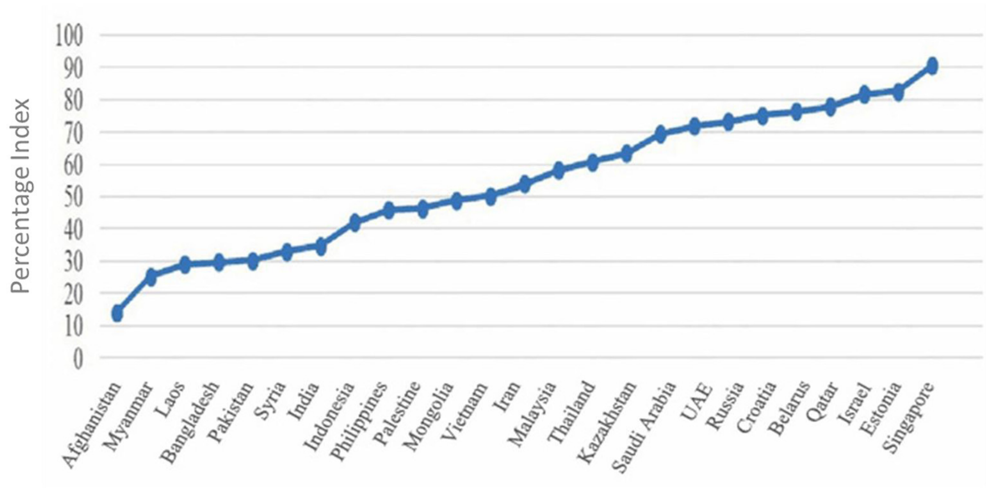

FIGURE 1
Development level indexes of B&R countries.

six sub-indicators, including whether the parties have signed an investment agreement (bit), whether the investment agreement is in force, the degree of investment resistance, bilateral political relations, trade dependence, investment dependence, and visa exemption. Considering the availability of data and the comparative analysis that follows, the investment dependence of the host countries in the Kronecker system was determined as an indicator measuring the bilateral economic distance in this study.

Institutional environments of host countries. To date, the WGI annually released by the World Bank, and the International Country Risk Guide (ICRG) published by the U.S. PRS Group are in a better position to assess the national institutions and investment risks. The ICRG has been described as "authoritative" and "highly predictive" in terms of risk rating. As approaches measuring institutional environment indicators vary across international rating agencies, the overseas investment risk assessment system adopted in this study is the same as that of CROIC, which measures the institutional environments of the host countries by the corruption level, government effectiveness, and political stability. The corruption level (cor) measures the degree of corruption in the political system. Government effectiveness (ge) measures the quality of public services, the efficiency of policy formation and implementation. In addition, political stability (ps) measures the frequency of regime change and government capability to implement introduced policies.

Agricultural total factor productivity (TFP) of host countries. Most of the existing studies measure and judge the regional TFP from a rather macroscopic perspective. Methods calculating the industrial TFP include the C-D production function, the L-P method, and the DEA-Malmquist index method among others. Subject to the availability of agricultural data outside China, an approximate TFP index was taken as a substitute variable and the study results of Tian (2020) were used.

Scales of markets of host countries. A larger market scale, an important factor in attracting foreign investment, is expected to bring more effective economies of scale and scope, maximize the benefits of the development and output of farmland in the invested country, which mirrors a country's economic performance and economic environment. The market scale of a host country is expected to be positively correlated with the scale of Chinese investment in the country's farmland expressed by the gross national product (hgdp) in this study.

Geographical distance. The First Law of Geography, according to Tobler (1970), is "everything is related to everything else, but near things are more related than distant things." The geographical distance between countries was expressed by the bilateral distance between capitals (discap) in this study.

Degrees of trade openness of host countries. The degree of trade openness (trade) of a host country was measured by the sum of the host country's export and import divided by GDP. For the sake of consistency in the magnitudes, algorithmization was done to the GDP of host countries and geographic distance indicators (Table 2). The impacts of the selected indicators on China's farmland investment in the B&R countries were measured objectively.

Model building

(1) Major limitations on empirical study

The driving factors of China's OFDI (or foreign trade) are often tested empirically by the gravity model (Kolstad and Wiig, 2012; Wei and Li, 2019). In terms of foreign trade, the trade

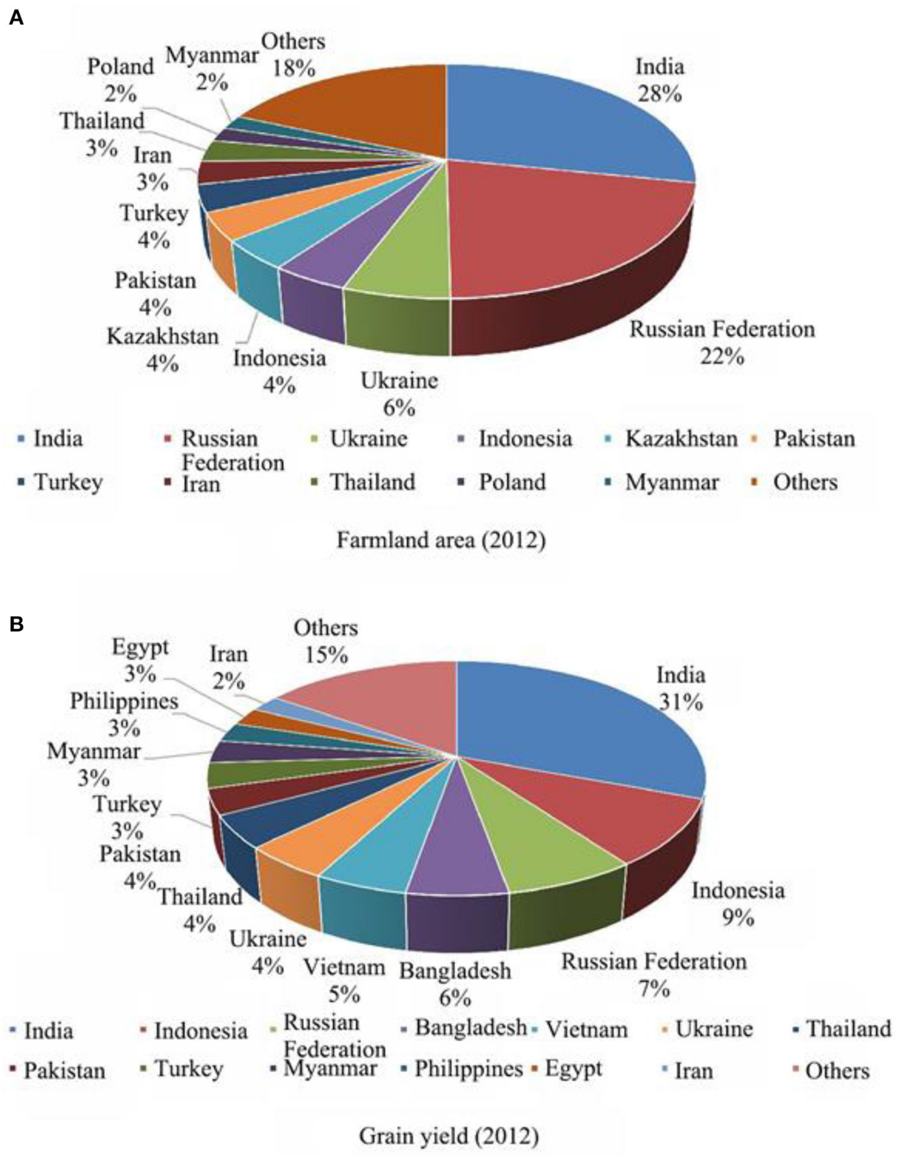

FIGURE 2
Spatial distribution of agricultural resource elements in B&R countries. **(A)** Farmland area. **(B)** Grain yield.

flow is used as the explained variable in some gravity models. However, Helpman et al. (2004) pointed out that there is no bilateral trade or only unilateral trade between most countries in transnational business activities. By analyzing the foreign trade data of different industries in the United States in 2005, Baldwin (2003) found that there is no trade in more than 90% of the data. The same is true with OFDI. Chinese enterprises make no investment in many countries (regions) in a certain year.

For example, an enterprise has not decided to make an investment in view of its own strength or project feasibility, or may quit after investing in the project, so that a large amount of farmland investment is zero in certain duration in the land transaction database. If parameters are estimated by the ordinary least squares after log-linearization in the traditional gravity model, the regression results will be biased because the conditional expectation of the error term is no longer equal to zero due to the change of the probability density function of the dependent variable and the existence of heteroscedasticity. Based on the above analysis, there is a limitation on the feasibility of the empirical approach in the study on the factors influencing China's overseas farmland investment, which is mainly reflected in two aspects: limited dependent variables and sample selection bias. (1) Limited dependent variable. Only farmland transaction data larger than 200 hectares is available in the updated statistical database of Land Matrix due to statistical reasons. In reality, most enterprises have not invested in overseas farmland or have not reached the collection scale of Land Matrix Database after investment. Therefore, there is a "left truncation" in China's overseas farmland investment at 200 hectares. In addition, enterprises may continue to invest to recover costs and seek profits after they are familiar with and adapt to the investment environments of the host countries due to the long cycle of farmland investment and high initial investment so that the target host countries of China's long-term farmland investment are concentrated in only a few countries, showing a non-normal distribution. Based on the above analysis, the enterprise first selects whether to invest in overseas farmland and then decides the scale and mode of investment. The explained variables in such decision-making behavior are limited to a certain extent, and the method of ordinary least squares is not applicable.

(2) Sample selection bias

If a sample survey is adopted for analysis, the data cannot explore the true investment behaviors of enterprises when there are no farmland investment activities or the investment scale is less than 200 hectares in the selected samples, as it is impossible to estimate whether it is caused by factors such as the institutional environment or transportation costs. If the samples without farmland investment are ignored, and only the countries where China has invested in farmland are studied to infer the parameters of the equation, the actual state of the dependent variables cannot be fully reflected by such a processing method, and the estimated results may also be biased. Because some "zero investment" does not occur randomly, but may be related to the variables in the model, the loss of valid information may be caused if these samples are ignored (Hao and Ma, 2012). Rauch and Trindade (2002) believed that the method of ignoring countries without trade in international trade is only suitable for random sampling surveys among some individuals. If these samples (countries without trade) are not random, the estimated results may be biased. In this study, if the host countries where China has made no overseas farmland investment are more concentrated in the B&R countries with scarce farmland resources or long bilateral distances, the impacts of the farmland resources in host countries on China's overseas farmland investment will be underestimated when the samples of these countries are ignored, misjudging the determinants of the location selection of China's overseas farmland investment.

(3) Model selection

In the actual studies of social science data, many null values are found often in the number of observed events. For example, widespread attention from multidisciplinary fields has been paid to data on hospitalization, prisoners, birth, abortion, and other special discrete limited variables. Because there are too many null points in the atmospheric data, the same null points reflect different situations, and the atmospheric data often vary greatly. The zero-inflated negative binomial (ZINB) model is developed based on the denispoisson model and negative binomial model technology, in which the problem of excessive null points in count data is explained, making it possible to identify the true null point of dependent variables, obtaining reliable hypothesis testing and parameter estimation, and helping researchers to solve a series of practical problems that cannot be solved by traditional models.

(4) Model building

In the zero-inflated count model, the mixed probability distribution composed of zero count and non-zero count sets is:

$$y\begin{cases} 0, pi \\ g(yi), 1-pi \end{cases} \tag{1}$$

In Formula (1), y represents the number of events in the sample data, i.e., the number of China's farmland investment in host countries; P represents the probability that there are too many "0"s in the data when the individual comes from the first process and follows the Bernoulli distribution; $g(yi)$ means that the individual comes from the second process and follows Poisson distribution or negative binomial distribution, with the probability of 1-P. In terms of the copula function, the logit function was used in this analysis, and the final model obtained is as follows:

$$\text{ofid} = \alpha_0 + \alpha_1^{*}\text{res} + \alpha_2^{*}\text{control} + \varepsilon \tag{2}$$

Where α_0 is a constant term, α_1-α_2 are regression coefficients, and ε is a random error term.

Empirical analysis

(1) Descriptive and correlation analysis

A descriptive analysis of the variables in this study was performed at first before the regression analysis, to list their basic statistical characteristics and perform correlation analysis.

The descriptive analysis is shown in Table 3, in which the maximum, minimum, mean, standard deviation and median of each variable are listed.

The results of the correlation analysis are shown in Table 4. The Pearson correlation analysis method was adopted. According to the results of this study, farmland investment (ofdi) and farmland resources (res) were significantly positively correlated, with a correlation coefficient of 0.415, which was significant at the level of 1%. In terms of control variables, farmland investment (ofdi) was significantly negatively correlated with the degree of corruption (cor), government effectiveness (cor), and the distance from Beijing to the host country (discap). The farmland investment (ofdi) was significantly negatively correlated with political stability (PS), and agricultural approximate TFP (atfp) was significantly positively correlated. However, the correlation analysis is only the single-factor analysis, and the correlation between the final variables shall be determined by multiple linear regressions. In addition, collinearity also can be determined by the correlation

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TABLE 2 Definition of variables.

Variable type	Variable symbol	Variable name	Source
Explained variable	ofdi	Farmland investment (10,000 ha)	Land Matrix Database GRAIN, 2012, 2015; Sun et al., 2018
Explaining variable	res	Farmland resources	Tian, 2020
Control variable	cor	Corruption—higher scores indicate a higher corruption level	Country-Risk Rating of Overseas Investment from China (CROIC)
	ge	Government effectiveness—higher scores indicate more effective government	CROIC
	ps	Political stability—higher scores indicate less stable government	CROIC
	diseco	Economic distance	CROIC and World Bank Database
	atfp	Agricultural proximate productivity	Tian, 2020
	discap	Distance from Beijing to the host countries	CEPII
	hdgp	Market scale of the host countries	World Bank Database
	TRADE	Host countries' total volume of import and export trade as a share of GDP	World Bank Database

TABLE 3 Descriptive analysis.

	Figure	Min.	Max.	Average	Standard deviation	Median
ofdi	480	0.0000	58.7000	1.8134	6.8470	0.0000
res	480	0.0004	0.6759	0.0724	0.1193	0.0318
cor	480	1.0000	4.5000	2.2144	0.7269	2.0000
ger	480	−1.6500	2.4300	−0.0282	0.9466	−0.2000
ps	480	4.0000	11.0000	7.3756	1.3500	7.3000
diseco	480	0.0000	0.8001	0.0909	0.1712	0.0120
atfp	480	3.3523	19.9253	9.5664	2.0091	9.6849
discap	480	1,783.0820	8,064.5690	5,791.9493	1,840.4285	6,392.8365
hdgp	480	22.2458	28.6066	25.0158	1.4345	24.9354
TRADE	480	0.0000	10.4401	1.1625	1.6537	0.7020

TABLE 4 Correlation analysis.

	ofdi	res	cor	ger	ps	diseco	atfp	discap	hdgp	TRADE
ofdi	1									
res	0.415**	1								
cor	−0.194**	−0.044	1							
ger	−0.155**	−0.125**	0.373**	1						
ps	0.105*	−0.094*	0.219**	0.001	1					
diseco	0.064	−0.049	−0.123**	−0.054	−0.008	1				
atfp	0.189**	0.476**	−0.243**	−0.468**	−0.182**	0.038	1			
discap	−0.231**	−0.263**	0.081	0.137**	−0.102*	−0.074	−0.250**	1		
hdgp	−0.066	0.408**	0.361**	0.248**	−0.079	−0.096*	0.135**	0.116*	1	
TRADE	−0.052	−0.101*	0.255**	0.319**	0.141**	−0.027	−0.360**	−0.107*	0.074	1

*The correlation was significant when the confidence coefficient (double test) is 0.05.
**The correlation was significant when the confidence coefficient (double test) is 0.01.

TABLE 5 Collinearity test.

Variable	VIF	1/VIF
atfp	1.93	0.52
hdgp	1.67	0.60
res	1.66	0.60
ge	1.57	0.64
cor	1.45	0.69
trade	1.29	0.78
discap	1.27	0.79
ps	1.14	0.88
diseco	1.03	0.97

TABLE 6 Regression results.

ofdi	Coef.	Robust Std. Err.	z	$P > z$
res	9.9600	1.3040	7.6400	0.0000***
cor	−1.5670	0.3570	−4.3900	0.0000***
ge	−0.2520	0.2340	−1.0800	0.2810
ps	0.2050	0.0820	2.4900	0.0130**
diseco	0.8480	0.6160	1.3800	0.1690
atfp	0.0040	0.0840	0.0500	0.9630
discap	−0.00002	0.0000	−6.6200	0.0000***
hdgp	−0.5980	0.1400	−4.2700	0.0000***
trade	0.1390	0.0840	1.6500	0.0990*
_cons	16.7380	3.1420	5.3300	0.0000***
N	480			
Wald chi2(9)	370.77***			
Pseudo R2	0.6061			

*, **, and *** means it was significant at 10%, 5%, and 1%, respectively.

analysis. Generally, it is believed that there is collinearity and the results of the regression model are biased if the correlation coefficients between the explaining variables, and between the explaining variable and the control variable are all more than 0.8. According to this result, the correlation coefficients were less than 0.8, indicating that there was no collinearity, and further regression analysis could be performed.

(2) Collinearity test

The Variance Inflation Factor (VIF) method was used herein to test whether there is multicollinearity among variables before the formal regression analysis was performed. The calculation results showed that the variance inflation factor of each variable was less than 10 (Table 5), indicating that there was no serious multicollinearity among these 9 variables, which can be used in the empirical test herein.

(3) Regression analysis

The above variables were substituted into the model in this section, and the zero-inflated Poisson model and Stata15.0 analysis software were used to perform empirical analysis on all samples.

The regression results are shown in Table 6. Pseudo *r2* was used to judge that the model fits well, and the value range was 0–1. The closer it was to 1, the better the model fitted. Pseudo *R2* was 0.6061 in this study, which indicated that the model fit well. The value of Wald chi2(9) was 370.77, and there was a significant difference at the level of 1%, indicating that the model fit.

The full-variable model was applied in this study to test the impacts of variables on the farmland investment scale in the B&R countries. The regression equation included explaining variables-farmland resources, three indicators to measure the institutional environment of host countries, bilateral economic distance variables, economic distance and institutional environment, agricultural approximate TFP of host countries, etc. According to the results, the regression coefficient of farmland resources (res) was 9.9600, which was significant at the level of 1%, indicating that farmland investment (ofdi) and farmland resources (res) were significantly positively correlated. China's farmland investment (ofdi) in host countries has increased with the increase of farmland resources (res) within a certain range. The regression coefficient of the degree of corruption (cor) was −1.5670, which was significant at the level of 1%, indicating the farmland investment (ofdi) and the degree of corruption (cor) were significantly negatively correlated. China's farmland investment in host countries has increased with the decrease of the degree of corruption (cor) of host countries within a certain range. The regression coefficient of political stability (PS) was 0.2050, indicating that farmland investment (ofdi) and political stability (PS) were significantly positively correlated. China's farmland investment in host countries has increased by 0.2050% as political stability (PS) of host countries increased by 1%. The distance from Beijing to the host countries (discap) and the farmland investment (ofdi) were significantly negatively correlated. The farther the distance from Beijing to the host countries, the less China's farmland investment in the host countries. The economic scale of the host countries (hdgp) and the farmland investment (ofdi) were significantly negatively correlated. The smaller the economic scale of host countries (hdgp), the less China invested directly in host countries. The proportion of the host countries' total trade to GDP (trade) was positively correlated with farmland investment (ofdi). The higher the proportion of the host countries' total import-export volume (trade) to GDP, the more China's farmland investment in the host countries.

(4) Robustness analysis

The farmland resources herein were comprehensively calculated by several indicators related to the quantity and quality of farmland. As it was difficult to find effective instrumental variables and substitute variables, negative binomial Poisson regression was used for robustness analysis to further evaluate the effectiveness of the model regression. Currently, studies on the prediction of the incidence by the zero-inflated model mainly focus on population sociology, agricultural extension, and other fields. In the robustness test in Table 7, the impact direction and significance of all explaining variables almost maintained unchanged. This indicates that the regression results herein are reliable.

TABLE 7 Robustness results.

ofdi	Coef.	Robust Std. Err.	z	P > z
res	9.1780	1.0380	8.8400	0.0000***
cor	−2.7360	0.3340	−8.2000	0.0000***
ge	0.2000	0.3370	0.5900	0.5530
ps	0.3330	0.1160	2.8700	0.0040***
diseco	1.0460	0.8310	1.2600	0.2080
atfp	0.4680	0.2750	1.7000	0.0890*
discap	−0.0010	0.0000	−7.9000	0.0000***
hdgp	−0.3210	0.1290	−2.4800	0.0130**
trade	−0.0720	0.0860	−0.8400	0.4020
_cons	9.1630	2.7710	3.3100	0.0010***
N	480			
Wald chi2(9)	320.49			
Pseudo R2	0.2543			

*, **, and *** means it was significant at 10%, 5%, and 1%, respectively.

Conclusion

(1) Impact of variables in the investment scale model

According to the pragmatic results, the location selection of farmland investment is significantly impacted by the economic distance, corruption level, and geographical distance of host countries to China. According to the empirical results of the investment scale model, important factors that affect the scale of China's investment in the B&R countries include farmland resources, corruption level in host countries, the agricultural approximate TFP, and geographic distance.

The regression coefficient of the economic distance from host countries to China (diseco) passed the significance test. The probability of Chinese enterprises' overseas farmland investment will decrease by 0.00002 percentage when the economic distance from host countries to China increases by one percentage, which validates the hypothesis. Frequent and large-scale economic exchanges between countries contribute to form unique bilateral social relations, thereby reaching a consensus on economic issues, helping to reduce the disadvantages of Chinese enterprises' overseas farmland investment as foreigners, reducing transaction costs of enterprises, and ultimately increasing the probability of investment. At the stage of investment scale decision-making, multinational agricultural enterprises themselves have already benefited from a close economic distance, so economic distance has no significant impact on the scale of local investment by enterprises.

The coefficient of the corruption level (cor) of host countries has a negative impact in the model, which is significant at the significance level of 5%, so that the hypothesis is supported. With the establishment of China's modern enterprise system and the participation by more private enterprises, Chinese enterprises have paid more attention to market-oriented investment in overseas farmland, so that they tend to avoid risks in farmland investment. This result is consistent with the study conclusion of Wan and Lu (Gao et al., 2013), refuting the conclusion that Chinese enterprises prefer to select locations with a higher risk of corruption for their overseas investment pointed out by some international scholars. In view of the long process of farmland investment, the government of the host country manages the farmland transactions of multinational enterprises, so that the conflicts that may occur in the follow-up of farmland management projects can be mediated effectively. It is believed in this study that the host countries' institutional environments have always been an important factor influencing the investment scale in the long run.

The variable of farmland resources (res) of the B&R countries is positively correlated with the investment scale of enterprises, which is consistent with the intuitive results observed above that the countries with abundant farmland resources are associated with destinations of China's farmland investment. It is noted that farmland resources are attractive in terms of the location selection of China's farmland investment in the B&R countries to some extent, but it is not a determinant. The farmland resources are of greater importance for the investment scale decision-making, that is, enterprises pay more attention to the continuous supply of input elements required for grain production during the stage of scale decision-making. Therefore, farmland resources of host countries (including the quantity and quality of farmland) play a highly significant and positive role in promoting the scale of farmland investment, which supports the hypothesis.

Agricultural approximate TFP (aftp) has no significant impact on the stage of location selection of enterprises' farmland investment. This indicates that although the agricultural approximate TFP has little effect on the probability of China's farmland investment in the B&R countries, the post-investment scale of enterprises in host countries will be reduced by higher productivity. Upon cause analysis, the potential for future development of agriculture lies in the improvement of agricultural TFP under the condition of limited natural resources. Both the progress in agricultural technology and the optimal allocation of resources may play role in promoting the agricultural TFP (Li and Fan, 2013; Hao and Zhang, 2016). In terms of agricultural production, with cutting-edge technology and rich experience in management, Chinese enterprises prefer to expand the scale of farmland investment in countries with low productivity after deciding to invest, so as to give better play to their comparative advantages.

The coefficient of the market scale of the host country (lnhgdp) is significantly negatively correlated in the model, which is different from the research conclusion of Hao and Zhang (2016), that is, with obvious market seeking characteristics of China's overseas farmland investment now, the scale of farmland investment is larger in host countries with a smaller economic scale.

The geographical distance (discap) variable is negatively correlated at the level of 1% in the location selection and investment decision-making model, and the significance of its impact is one of the most stable and obvious variables. This is consistent with the research results of other scholars, and also confirms that the long geographical distance is unfavorable to the operation and management of overseas farmland investment and the transportation of agricultural products so that this variable has a significant negative impact in each model.

The coefficient symbol of the trade openness (trade) is positive, which is significant at the level of 10%. One possible explanation is that some of the crops that China invests in and plants in host countries are exported by enterprises taking advantage of geography or more convenient policy environment in host countries, while some are directly sold locally. The trade openness of host countries has little effect on China's overseas farmland investment behavior based on the study samples and periods herein.

Driving factors of overseas investment

Markets seeking overseas investment

Firstly, sufficient services about information of the B&R countries are provided by China to Chinese enterprises, so that the enterprises willing to participate in OFDI can easily and freely access relevant information, thus greatly reducing the costs and difficulties in the production and operation of Chinese enterprises in the host countries, and improving their OFDI capabilities. Secondly, the return on investment of enterprises can be directly increased by tax incentives. Tax incentives are provided by the Chinese government to the OFDI enterprises of China, which can not only directly increase the net investment return of Chinese enterprises in the host countries, but also promote the OFDI of Chinese enterprises, so that such enterprises have more funds for daily turnover and reinvestment, and their investment capabilities are is further enhanced. Thirdly, strong financing support has been provided by China for its enterprises as OFDI requires large amounts of funds. The financing support refers to China's support for Chinese enterprises in raising funds for OFDI, including the raising and distribution of financing funds and subsidies for financing costs. Such financing support can satisfy the capital demand of Chinese enterprises, ensure that they have adequate capital for OFDI, reduce their financing costs, and improve their profitability and return on investment, thereby boosting their enthusiasm for OFDI. Financing is one of the "Five Connectivity" programs of the Belt and Road Initiative proposed by China, namely, China will lead the Silk Road Fund, the Asian Infrastructure Investment Bank, the China Development Bank, the Export-Import Bank of China (EIBC), and the four major Chinese banks (Bank of China, Industrial and Commercial Bank of China, Agricultural Bank of China, China Construction Bank) to provide adequate financial support for the Belt and Road Initiative and significantly enhance the investment capabilities of participating enterprises.

Technology seeking overseas investment

The knowledge spillover from the export trade created by China's OFDI in the B&R countries cannot be ignored. A value transfer mechanism exists in the global value chain. In the study of Pakistani enterprises, the technological levels of local suppliers are enhanced by embedding them into the global value chain. The embedding of the local innovation system into the global value chain marks a great opportunity for the technological advancement of relevant countries. Chinese enterprises generate a competition effect on downstream enterprises, namely, investment enterprises are willing to assist downstream enterprises in management training, marketing planning, and market exploration in order to increase their brand impact and market shares, and increase returns to scale (Kolstad and Wiig, 2012). The realization of technology spillover also requires certain absorption capabilities of the host countries. Among them, the strength of scientific and technological research and development is the primary prerequisite, and such strength of the B&R countries varies greatly, and the capabilities to absorb and expand technology spillover determines the realization of technology spillover and the scale of its effect (Li and Fan, 2013).

Factors of the value chain

Within the framework of cooperation under the Belt and Road Initiative, China will work even more closely with the B&R countries in scientific and technological cooperation to improve the level of cooperation in key fields with scientific and technological advantages and demands, and further establish scientific and technological cooperation mechanisms with the B&R countries, which is conducive not only to breaking technological discrimination and blockade in key scientific and technological fields but also enhancing China's voice and right to call in scientific and technological fields, escorting the economic, trade and cultural exchanges of the B&R countries. "Pulled" by the import demands of technically backward countries and "pushed" by China's industrial upgrading, the technology is transferred from the technological "highland" with China at the core to the technological "lowland" with emerging-market countries at the core along the "Belt and Road". Since the Belt and Road Initiative was proposed, China's participation in the global industrial division and the creation of value systems has been furthering, and China's technology transfer to the emerging markets along the Belt and Road indicates that the traditional direction of technology diffusion has changed from "developed countries to emerging markets" to "developed countries and emerging markets to emerging markets".

Impacts of concentration of overseas investment location selection

Concentration of overseas investment location selection and development of enterprises

In terms of natural resources, if the enterprises need to obtain resources from the B&R countries for their production and operation, they can internalize the resource transactions of the B&R countries through OFDI in order to avoid tariff barriers or exchange rate fluctuation risks, so as to reduce the production costs, maintain the stability of production and operation, and provide continuous financial support for research, development, and innovation. Therefore, Chinese enterprises are more likely to obtain reverse technology spillovers through the research and development cost sharing channels when making OFDI in said countries with rich natural resources. In terms of the national institutions, different institutional environments of the B&R countries may differently impact the relationship between OFDI and innovation of Chinese enterprises. On the one hand, the better the institutional environments in the B&R countries are, the lower the operating costs are and the more stable the operating profits of Chinese enterprises are, so the sharing methods of research and development costs can be utilized to promote technological innovation of Chinese enterprises. On the other hand, the worse the institutional environments in the B&R countries are, the more likely Chinese enterprises are to obtain implicit income through rent-seeking behaviors, so as to provide financial support for research and development of Chinese enterprises and improve their innovation capabilities. As for geographical location, the closer the geographical distances between China and the B&R countries are, the lower the transport costs, transaction costs, and fixed production costs of OFDI will be, which will effectively share the research, development, and production costs of Chinese enterprises (Hao and Zhang, 2016). Therefore, the OFDI in the B&R countries with relatively close geographical distances can promote innovation of Chinese enterprises through the research and development cost sharing channels. According to statistics, as for OFDI in the B&R countries, China mainly invests in close ones, such as Singapore, Kazakhstan, Indonesia, and Russia. Griliches pointed out that from the perspective of cultural distance, studies had shown that the role of the cultural distance of host countries in the relationship between OFDI and innovation of home country was uncertain, either as a catalyst or as a hindrance. However, the B&R countries are characterized by highly diversified religious cultures, including almost all types of religions. The B&R countries differ greatly in their economic development, scientific and technological levels, institutional environments, religious beliefs, cultural customs, and other characteristics, which provides opportunities for Chinese enterprises to participate in the scientific and technological innovation cooperation of Belt and Road, and may also bring about potential conflicts and risks.

Concentration of overseas investment location selection and development of industries

From the aspect of technology, China's direct investment in the B&R countries will generate a positive spillover effect on the recipient countries. The participation of the B&R countries in the global value chain is an important opportunity for them to realize technological upgrading, and the absorption of knowledge and technology spillovers will help them develop innovative technologies and increase industrial added values. The B&R countries are mainly developing economies, with large entry barriers in most of their advantageous industries. The entry of Chinese enterprises may change the original market structures of the host countries, thus intensifying industrial competition, forcing the enterprises of the host countries to increase research and development expenditure, cultivating the local industrial chains, combining the global industrial chain with the local industrial chains, and finally promoting the technological progress of the host countries to develop toward the direction of high-value-added industries.

Suggestions on location selection for China's OFDI

Selecting diversified overseas investment locations

The overseas investment locations of China are very concentrated geographically. It is necessary to consider the regional flow that spreads the overseas investment in order

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to decentralize the investment risks, promote the optimal allocation of resources, and increase the return on overseas investment. According to different investment objectives, regional strategies at different levels should be diversified for China's overseas investment. Since there is a huge market for China's products in developed countries, developed countries often implement strict trade protection measures and more investment policy restrictions. For China's overseas investment enterprises seeking markets, the ideal overseas investment path is to directly invest in the developing countries around the developed countries and then export their products to corresponding developed countries in such an indirect way. In this way, not only can the market shares of developed countries be effectively expanded, but also the low cost advantage of developing countries can be utilized to reduce production costs, but attention should be paid to the principle of origin adopted by developed countries. In addition, overseas investment enterprises with a certain foundation can directly invest in the target countries after accurately targeting the target market. For some weak enterprises with insufficient investment experience, if they excessively rely on the markets, they must comprehensively consider and analyze the geographical concentration of industrial investment in a detailed manner, avoid areas with fierce competition, take into account their actual conditions and directly invest in the regions with large market growth potential. The location selection of resource-based OFDI is relatively clear and the major investment targets should be countries and regions with abundant resources, low mining costs, and low access thresholds. Generally, the locations of such investment enterprises are relatively stable, but for new investment enterprises, full consideration should be given to the concentration of locations for seeking resource-based overseas investment, in order to avoid similar enterprises from competing for limited resources in the same region, and shall select target locations in countries and regions with abundant resources and few investment enterprises. These investments should be targeted at developed countries since these technologies, especially information technology, are largely concentrated in a few countries and regions, such as the United States, Japan, and the European Union. In terms of the specific arrangement of investment path, the focus of investment of Chinese enterprises should be placed on the technical research, development, and management of products, rather than the production and processing of products. Through direct investment, technology research centers and government sales management research centers will be established to give full play to the spillover and agglomeration effects of technology research and development in developed countries. The study-based overseas investment is mainly concentrated in the high-tech industries. Multinational enterprises in China can consider the location concentration of foreign investment, make use of the agglomeration effect within the industry, strengthen the cooperation and exchange between enterprises, and realize the maximum benefits of foreign investment.

Adjusting the location concentration of relevant industries

China's overseas investment involves a wide range of industries, with an increasingly obvious trend of diversified development. However, the distribution of overseas investment in the industries is still unreasonable. The location concentration of overseas investment in some industries is very high, which tends to lead to the homogeneity of investment in some industries. A necessary means to solve this problem is to adjust the location concentration of overseas investment in related industries. The location selection of overseas investment should be combined with industrial development, and the location strategy should be reasonably arranged according to the characteristics of industrial development and the current status of location distribution of overseas investment.

First, mature and applicable technology industries. The mature and applicable technology industries refer to the industries with the technology advantage of scale in China, but their investment profits decrease and their products face elimination in China's market. The investment location selection of these industries is relatively concentrated. In order to reduce the location concentration and in combination with the characteristics of industrial development, such investment can be located in markets with a higher demand but a lower level than China, such as developing countries around West Asia and in Southeast Asia, and countries with slightly higher economic levels in Latin America and Africa, so as to transfer "marginal industries" and upgrade domestic industries of China.

Second, the first processing and manufacturing industry with certain comparative advantages. This industry requires little overseas investment and has a short cycle and quick effect, so it is especially suitable for the development model of small and medium-sized enterprises (SMEs). For China's overseas investment, the labor-intensive industries should be gradually replaced by technology-intensive industries, but this change should be analyzed in combination with different regions. This industry is also one of the key investment industries of China. Firstly, there is an obvious feature of location concentration. It is necessary to appropriately reduce the concentration within the industry and reasonably select the locations. For the investments in developed countries, it is required to change the current pattern of labor-intensive industries and optimize and upgrade invested industries as soon as possible. However, for the investments in countries with low levels of economic development, it is required to

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gradually keep pace with the upgrading of the domestic industrial structure in China, and gradually transform from the development of traditional labor-intensive industries to the development of technology-intensive industries. Distinguishing the investment distribution of the above two regions can effectively reduce the location concentration of overseas investment in this industry.

Third, overseas investment in the high-tech industry. Developed countries own high-quality human resources, can produce high-quality products, improve the TFP, and show powerful location advantages in high-tech products or industries, so it is suitable for the development of high-tech industries. The investment of related enterprises in China is increasing gradually with the rapid development of China's high-tech industry. China possesses the ability to invest and operate in developed countries since the research achievements in microelectronics, bioengineering, materials industry, aerospace, and other industries are world-leading. The international operation can also promote the rapid development of domestic industries in China. However, generally, most enterprises of China are weak in transforming scientific and technological achievements into productive forces. Therefore, the Chinese government should offer certain policy support, encourage and protect the domestic enterprises to participate in the international market competition, and promote the optimization and upgrading of the domestic industrial structure. This type of investment generates a strong concentration effect. As China's investment in this industry is not large enough, it is necessary to give full play to the concentration effect of investment, appropriately increase the concentration of overseas investment in this industry, and urge relevant Chinese enterprises to invest abroad.

Fourth, overseas investment in the capital-intensive and technology-intensive manufacturing industry. China can make direct investment in industries in which China has potential competitive advantages in developed countries, bring its own industries closer to advanced technological resources, carry out production and operation in accordance with international practices, and participate in international competition at a higher level. Fifth, overseas investment in the resource and energy industry. The OFDI is concentrated in this industry since the geographic distribution of world resources is very clear. In order to realize the optimal allocation of resources, domestic enterprises in China should take the occupation of resource locations and markets as the baseline when they invest in the industry. Meanwhile, the government should also exert control so that the enterprises investing in the resource and energy industry are distributed in more reasonable regions to avoid the vicious competition of resources and energy development. In short, the industrial development must be combined with the location selection as for China's OFDI, so as to develop different industries for countries of different economic development levels and promote the rationalization of the location concentration of overseas investment.

Improving the location layout of the value chain

The value chain as a management analysis method is utilized to analyze various economic phenomena more and more in economics. In recent 2 years, from the perspective of overseas investment, China's overseas investment tends to shift to the value chain with high added values, but most enterprises still focus on processing trade, price competition, OEM, and low-end products, which determines their position at the lower end of the value chain. The technological development capability of Chinese enterprises is poor and the core technology and products are imported, which are the main causes of the weakness of the core competitiveness of Chinese enterprises. To improve the position of Chinese enterprises in the value chain, it is necessary to cultivate independent brands based on the improvement of product quality, fully utilize the foreign resources and advantages, make up for the deficiencies of some of their links in the value chain, and realize the integration of the global value chain According to the enterprise value chain, the location selection requires separating different links in the enterprises, utilizing the location advantages of host countries in each link, and arranging these links in the most suitable countries and regions for their development. This in fact puts forward a certain requirement to the conditions of the enterprises that the enterprises must be of a certain scale and can divide the production activities into different procedures and links. Few overseas investment enterprises of China can meet this requirement, but qualified enterprises can optimize their geographical distribution around the world according to the concept of the value chain and promote the development and growth of enterprises by optimizing and combining different production links and regional characteristics. The location arrangement of the enterprise value chain decentralizes the overseas investment in different regions of the world, reasonably allocates resources, and disperses management risks.

Exerting superiority of concentration to promote clustered overseas investment

China's overseas investment enterprises show a trend of centralized development in terms of location selection. Generally, this selection will bring about a positive effect of enterprise cluster. In practice, however, although Chinese enterprises are concentrated, they do not attach importance to the connection between groups and division of labor and cooperation, the effect of concentration is not brought into play, and the regional concentration does not bring the advantage of centralized development. In recent years, the overseas investment of China's SMEs has gradually developed, and the development model of cluster investment is conducive to enterprises to make full use of the advantages of regional concentration, effectively avoid unfavorable factors, and promote the healthy development of China's overseas investment. In order to promote the cluster overseas investment of SMEs, the government should first formulate corresponding public policies to provide convenience for the financing of SMEs, help investors deal with the daily financial business, and strengthen the financial support. In the process of promoting the cluster overseas investment of enterprises, the emphasis should be placed on cultivating core enterprises, promoting the common development of other enterprises within the group, promoting the formation of specialized division of labor, and improving the production efficiency of enterprises. Meanwhile, it is necessary to pay attention to technological innovation, avoid excessive competition due to the homogenization of enterprises, and make the enterprises in the group realize the differentiated common development of products and services through innovative technologies and concepts.

Conclusion

(1) The scope of land property rights in the definition of land property rights in the host countries is the decisive premise of transnational land transactions. There are many uncertainties in the current international situation, including the sustainability of rapid economic growth, increasing constraints on productive resources, land degradation, water consumption, increasing climate change, bilateral distance, etc. These uncertainties may potentially affect crop yield fluctuations, which may lead to changes in host countries' rules on foreign ownership and farmland contracting. Therefore, the transnational enterprises of farmland investment need to pay close attention to the land policies of the host countries.

(2) The stages of location selection and scale decision-making of China's farmland investment in major B&R countries are impacted by different factors. In the stage of location selection, enterprises should pay more attention to countries with a closer bilateral distance and a better institutional environment. The bilateral distance is vital for transnational enterprises. However, it is even more important for transnational enterprises that invest in farmland, since farmland investment involves large initial sunk costs and a high degree of uncertainty in the external environment. Therefore, to some extent, a closer bilateral distance means a more stable and predictable business environment. In the stage of scale decision-making, on the one hand, enterprises should continue to pay attention to the institutional environments of the host countries and natural resources are strategically, politically, and financially important for the host countries. Therefore, the governments strictly control the OFDI in natural resources, and enterprises have to deal with the governments of host countries continuously throughout the investment process. The empirical results of this study further highlight the importance of the host countries' institutional environments. Olivia (2003), Bbsse and Hefeker (2007), Quer et al. (2012), Guo et al. (2014) and other scholars have similar conclusions. In order to cope with the political risks of the host country, foreign agricultural direct investment enterprises should improve their ability to identify, warn and respond to the political risks of the host country, scientifically screen the information released by the outside world, do a good job in the investigation and political risk assessment before the project investment, as well as the dynamic monitoring and emergency plan of political risks during the project operation, so as to minimize the possible losses caused by political risks. On the other hand, the agricultural production technology in some countries is backward, there is great growth potential in the infrastructure markets, and the sharing of agricultural technology and the investment in engineering projects by Chinese enterprises have complementary advantages in investment cooperation for some countries that are in urgent need of developing agriculture. Therefore, the popularization of China's agricultural technology can promote the productivity of the host countries, thus improving the resource allocation efficiency of farmland exploitation, which is also one of the driving factors for Chinese enterprises to continue to operate and expand the investment scales in the host countries. Foreign investment in agriculture has become an inevitable choice to alleviate the contradiction between the shortage of agricultural resources and the structural shortage in various countries and build a community of interests and destiny. Countries should strengthen the strategic planning of agricultural foreign investment, and implement the strategy of agricultural science and technology first, agricultural investment and agricultural products trade simultaneously. Adopt a fair and inclusive investment model, take into account economic, social and environmental interests, promote poverty reduction and economic development through agricultural investment, and cooperate with relevant interest groups for win-win results.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

JT and YL each wrote the section of the manuscript, contributed to data curation and analysis, and contributed to the manuscript revision. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Does income imply food security in coffee growing communities? A case study in Yayu, Southwestern Ethiopia

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The impacts on food security of a transition from agriculture focused on local consumption to the participation in global markets are uncertain, with both positive and negative effects reported in the literature. In Ethiopia, coffee production for global markets has attracted growers from across the country to the coffee-forest zones. From a national perspective, the area is not a priority for food security enhancement, as financial indicators suggest food sufficiency. In this setting, we collected food security and dietary intake data from a total of 420 (3X140) units of households, non-breast-feeding children under 5 years, and women of reproductive age. Sampling was done in two-stages, a random selection of 300 households (out of a total of 4,300) Yayu, followed by sub-sampling of households with a child and woman meeting the above-mentioned criteria. Samples were used to determine a number of food and nutrition security indicators. More than 83% of the households were found to be hunger-free in the shortage season, but dietary diversity was suboptimal. More than 50% of children under 5 years of age and women lacked foods containing heme iron in the surplus season and 88% in the shortage season. Household food security during the surplus season did not depend on income, but wealth was significantly correlated ($p < 0.01$) with all of the food insecurity indicators except the "Body Mass Index" of target women in the shortage season. The strongest and weakest correlation was with the "House Food Insecurity Access Scale" (−0.85), and "Weight-to-Age *Z*-Score" (0.25), respectively. Overall, Yayu is not fully food secure, though the situation is better than average for the country. While household income helps in achieving calorific sufficiency, greater awareness of the relevance of dietary diversity and the local means to achieve it is needed to further improve nutritional status, regardless of the participation in global markets.

KEYWORDS

cash crop, coffee agroforestry, dietary diversity, food access, hidden hunger, nutrition security, seasonal food-insecurity, Yayu Biosphere Reserve

Introduction

Household financial capital and income can support Food and Nutrition Security (FNS), but its interaction with on-farm production of diverse and nutritious food can be complex. Since the "entitlement" concept of Sen (1981) and its endorsement as the "access" pillar became widely used in food security definitions (World Bank, 1986; FAO, 2009), two major viewpoints have been offered.

The first one affirms that integrating cash crops would effectively reduce rural poverty and positively contribute to FNS *via* enhancing income security of households and thus their acquisition of food in markets (Timmer, 1997; Pingali and Heisey, 1999; Jemal et al., 2018). Household income security is key particularly in areas dominated by cash crops while suffering periodic food shortages. In areas where cash crops dominate and terms of trade are favorable, farmers can outsource the production of cereal staples and pulses to other areas, and focus on the production of cash crops and some non-storable food crops (Govereh and Jayne, 1999, 2003; Brüntrup and Herrmann, 2010; Achterbosch et al., 2014; van Noordwijk et al., 2014; Kuhn and Endeshaw, 2015; Virchow et al., 2016). Furthermore, the integration of cash crops in the food production system contributes to the household FNS indirectly, through the combat of rural poverty and attainment of "healthy living" standards, while reducing vulnerability to the food shortage caused by environmental, market and other hazards, which are common to single crop-based farming systems. In addition, the economic improvement may stimulate the use of improved farming inputs and technologies, which ultimately augment the productivity and increase the sustainability of the food production system (Govereh and Jayne, 2003; Masanjala, 2006; Hashmiu et al., 2022). In other words, cash crops start a positive spiral out of poverty.

In contrast, a second viewpoint suggests that the introduction of cash crops will cause a negative impact on the smallholder farm households' food security, as it will compete for the means of production such as land, water and labor (Brüntrup and Herrmann, 2010; Kuhn and Endeshaw, 2015; Virchow et al., 2016; Jemal et al., 2021). Furthermore, the international demand for agricultural non-food products may influence strongly and displace the crops produced by small-scale farmers (Keyzer et al., 2005; Dose, 2007; Kuhn and Endeshaw, 2015; Virchow et al., 2016; Jemal et al., 2018; Andreotti et al., 2022). This competition may not only cause a decline in the quantity of food produced, but also deepen the fragmentation and degradation of land due to over-exploitation, which would contribute to food insecurity and poverty. Gender differentiation in control over the cash-crop income determines priorities for its use. Also, it is pointed out, that the reliability on purchased food can be hazardous, by the risks and high costs that the food marketing systems entail (Govereh and Jayne, 1999, 2003; Achterbosch et al., 2014). Moreover, the dominance of agricultural products cultivation for non-food is highly volatile, as their market is influenced by many external factors at different scales, which are fluctuating and unpredictable (Govereh and Jayne, 1999, 2003; Achterbosch et al., 2014; Jemal and Callo-Concha, 2017; Andreotti et al., 2022).

These contradicting viewpoints call for a detailed and contextualized analysis to propose adequate policy measures. For instance, in Ethiopia, which hosts more than 30 million of undernourished people (Birara et al., 2015; World Bank, 2021), a major policy effort to address FNS is the Productive Safety Net Program (PSNP), which targets episodic and chronic food-deficits at *woreda*[1] *level*, by reducing the vulnerability of households to food insecurity through encouraging their asset increase and promotion of environmental rehabilitation (Devereux et al., 2006; Berhane et al., 2014; Hailu and Amare, 2022).

But, data on people's nutritional status at *woreda*-level hardly exists (Rajkumar et al., 2012; Girma et al., 2021). For instance, in the west Gojam zone, identified by the PSNP as a food-secure area, a cross-sectional study estimated that 43.2% of the children under 5 years were affected by chronic malnutrition, and 49.2% were underweight (Teshome et al., 2009). Mekonnen and Gerber (2017) cross-checked data from 2004 to 2010 of six *woreda* from central Ethiopia, namely Bakko, Sibu-Sire, Lume, Adaa, Hettosa, and Tiyyo, to found out that none of them were considered food-insecure and included under PSNP, but about 27% of the household members had shown a borderline caloric intake (<2,100 kcal/day). These findings confirm that *woreda* identified as food secure might not necessarily be such, and current targeting may limit the effectiveness of the PSNP (Gilligan et al., 2008; Coll-Black et al., 2011; Berhane et al., 2014).

Furthermore, the PSNP identification of food insecure *woreda* essentially based on the households' economic status, implying that high-income was equivalent to the acquisition of the minimum caloric requirement, and the opposite, low income meant persistent food insecurity (MoARD, 2009). As result, many cash crop-sustained *woreda* were taken as food secure, implying that the income generated by selling these cash crops was essentially used for food acquisition. The Illubabor, Jimma, Keffa, and Sheka zones, which are the major coffee producing areas of the country (Gole, 2015; Jemal et al., 2018) were never labeled as food insecure (FEWS NET, 2002, 2004, 2005, 2009, 2011, 2013, 2015, 2017). Smallholder coffee growers of these areas contribute the largest share of the main export commodity of Ethiopia, coffee, whose annual export quantity

1 In Ethiopia, a woreda is the second smallest political-administrative unit. A woreda is composed by a given number of kebele, the smallest administrative political-unit.

and value reach 230,246 tons and 742, 823,000 USD (FAOSTAT, 2020).

These facts underline the guiding hypothesis of this study, that *woreda*-specific data on people's food and nutrition status could provide a more realistic backdrop for food security interventions, instead of taking the households economic status only. For that, this study aimed to disclose whether smallholder farm households in cash-crop dominated areas of Ethiopia are really food and nutrition secure, and did that by (1) determining the food security status, dietary habits and nutritional status of smallholder farm households of Yayu; (2) analyzing the variation in their food security status, dietary habits and nutritional status across seasons and household features in relation to social and economic assets.

Materials and methods

Location and study design

The Yayu Forest Coffee Biosphere Reserve is located between 8°10' – 8°39' N and 35°30'–36°4' E, in the Illubabor zone of the Oromiya state, Southwestern Ethiopia (Figure 1). The area was recognized by the United Nations Educational, Scientific and Cultural Organization (UNESCO) in 2010 for the *in-situ* conservation of wild *Coffea arabica*. It covers about 168,000 ha in six *woreda*, namely Algae Sachi, Bilo-Nopa, Chora, Doreni, Hurumu, and Yayu (Gole et al., 2009). The climate of the area is regarded as hot and humid, with mean annual temperature and precipitation values of 22.5°C and 2,100 mm, respectively (Gole, 2003). The Oromo ethnic group is predominant and is considered indigenous; but Amhara, Tigreway and Kembata people share the area in significant numbers, as they migrated from other parts of the country due to the government's resettlement program initiated in 1984 (Kassa, 2004).

The core livelihood of smallholder farmers in Yayu is coffee production (Gole et al., 2009), which is mostly carried out in three agroforestry practices: homegarden, multistorey-coffee-system and multipurpose-trees-on-farmlands. These involve up to 80 edible species of which 55 are primarily cultivated for the household food supply. Households' income emanate from farming (overall coffee production) in about 90% and the rest from off-farm activities (Jemal et al., 2018). In the last 15 years no incidents of food emergency have been reported in Yayu, thus labeled as food secure and never included in the PSNP (FEWS NET, 2002, 2004, 2005, 2009, 2011, 2013, 2015, 2017). Rather, the zone is regarded as a well-off and became a net destination for communities from other parts of the country, forced to relocate by their recurrent exposure to famines and droughts (Gizaw, 2013).

Sampling strategy

Eight kebele located in six *woreda* of the Yayu area were targeted based on their proximity to market/biosphere reserve as diversification criterion. Each kebele with a "core forest zone"[2] in its jurisdiction was marked as "near to forest," if not as "far from forest." Similarly, those *kebele* that were situated closer to the highway were supposed to have better access to markets, and considered as "near market," or else as "far from market." On this basis, every kebele in the reserve were grouped into four sets with two proximity factors each with two levels (near and far), and then two *kebele* from each group were selected subjectively based on their accessibility. Out of the 4,300 inhabitant households of the reserve area, a representative sample of 300 households were randomly selected, based on the information obtained from each of the six *woreda* administrative offices. Finally, 140 households having non-breast feeding (NBF) children under 5 years, and women of reproductive age (WRA) between 15 and 45 years of age, were subsampled for nutritional status evaluations. In case there was more than one child per household, the youngest was selected; and in the case of twins, the choice was randomly made (Mulu and Mengistie, 2017). Hence, a total of 420 sampling units of three different types, i.e., households, non-breast feeding children (NBF) under 5 years, and women of reproductive age (WRA), each with 140 units, were used for data collection.

Data collection

A household questionnaire, detailed dietary survey, and anthropometric measurements were applied as main data collection procedures. Surveys were pre-tested in 10 local households and adjusted before wider application. Originally prepared in English, the surveys were translated into *Amharic* and *Oromiffa* languages best known by the respondents. Responses were later translated back into English to crosscheck response accuracy. Household heads were asked for basic household information, except for the wealth ranking. Wealth ranking was collected from the data base of local *Kebele* administration, so that, a minimum within *kebele* subjective-error can be achieved through a locally developed ranking criteria. The person mainly responsible for food preparation in the household was asked for the food security and dietary history questions; as for the children, the main caregiver was asked. Dietary history survey and food security questions were asked at different times of the day to prevent confusion in the interviewees, and fatigue of the interviewees and interviewers.

2 The reserve consists of three concentric zones, i.e., core, buffer and transition zones, which unevenly occurred across the six woreda of the reserve. Many agricultural and-use types are tolerable only in the transition and buffer zones, but the inner most core zone is maintained as intact forests with no human activities permitted (Gole et al., 2009).

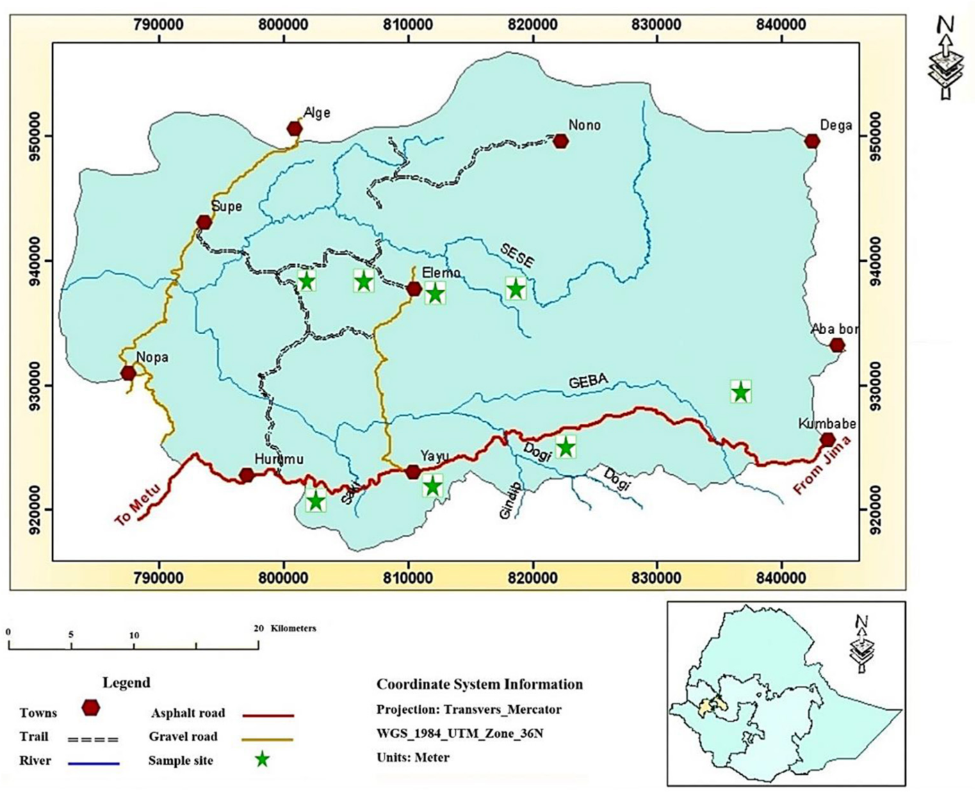

FIGURE 1
Map of Yayu in Ethiopia [adapted from Ilfata (2008)].

Female enumerators were recruited and trained among the local health extension agents; these were chosen based on their familiarity with dietary and anthropometric assessments, and ease of access to the target groups. Finally, all household heads, and parents or guardians in the case of children, were informed about the objectives and confidentiality of the study, and a verbal and written consent obtained. For the anthropometric measurements, electronic scales (with 100 g precision), and wooden collapsible length/height measuring devices (precision 1 mm) were used. The age of the children was captured considering month and year, whereas for women it was registered in years.

Five data sets were built: (1) **Basic household data**, which included age, educational status, gender, ethnicity, religion, settlement history, family size, and wealth rank. (2) Household food security status data, which included type, amount, and pattern of food consumed by householders during the past 4 weeks (Coates et al., 2007; Ballard et al., 2011). (3) Dietary intake/pattern data, including the household's consumption frequency of 12 food groups recalled for three-time references, i.e., 24 h, 7 days, and 4 weeks. (4) Dietary adequacy data, which refers to the type and frequency of food items consumed during the past 7 days by sensitive groups (NBF and WRA). Finally, (5) Nutritional status data, which compiled anthropometric records of NBF and WRA, such as body weight and height.

In Yayu, there are two main seasons in terms of food/cash surplus and shortage. Surplus occurs in the period after coffee and cereal crop harvest (between January and March), whereas shortage refers to the preceding time window from June to September, when the stock of the previous harvest is getting depleted and the next crop is not yet ready for harvest. So, data collection covered the two seasons and was gathered between December 2014 and August 2016.

Data analyses

By using the above mentioned five data sets, different scores, indices and statistics were calculated to estimate the four main food and nutrition attributes of the households (Figure 2).

Household food security status

It was assessed using three standard proxies, i.e., Household Hunger Scale (HHS) (Ballard et al., 2011), Household Food Insecurity Access Scale (HFIAS) (Coates et al., 2007), and

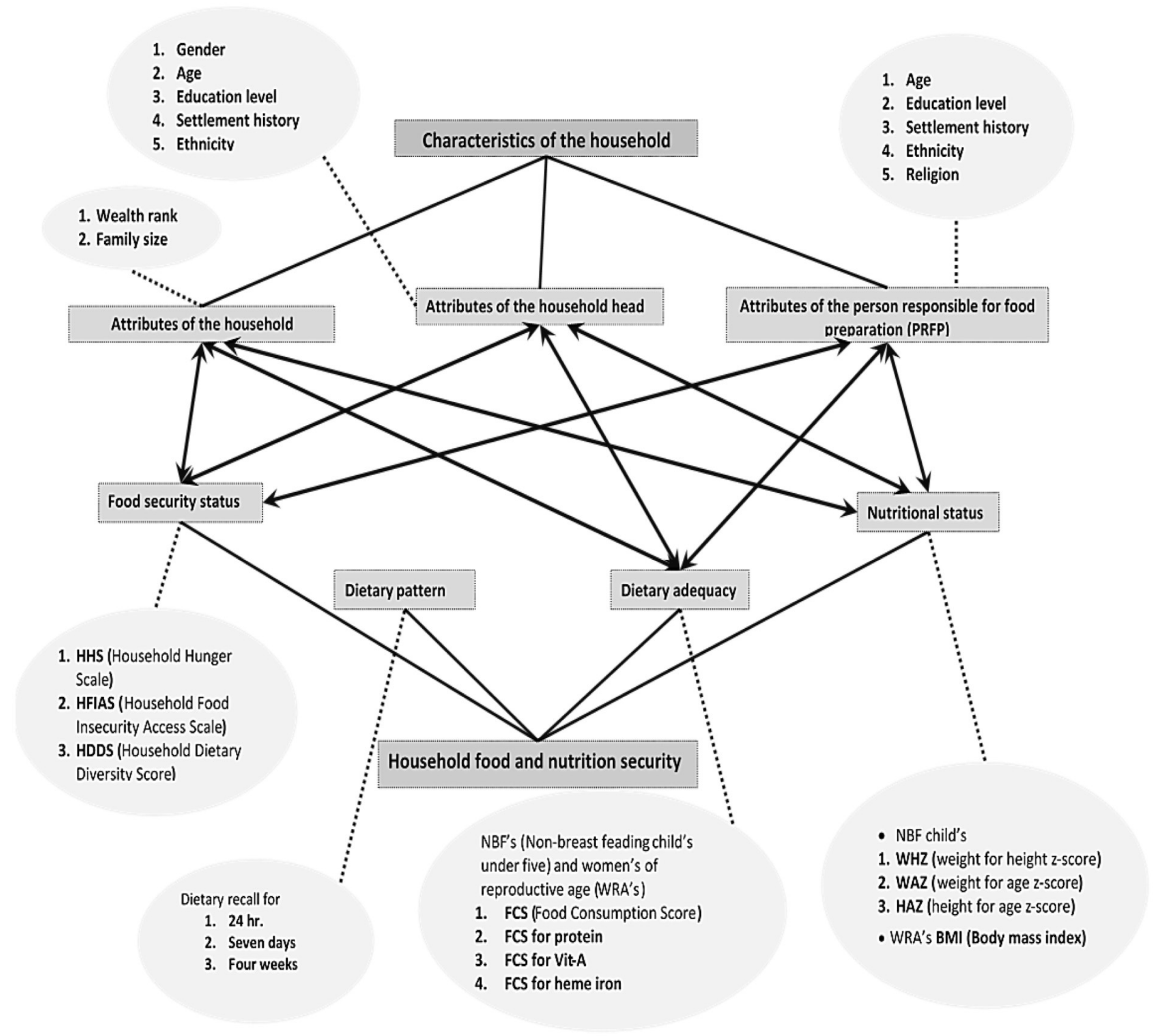

FIGURE 2
Data collection and analytical framework of the study. Broken lines connect each attributes and scores of the household to their respective indicator variables; solid lines connect two major aspects of household (characteristic and FNS) to their respective components; solid double arrow line show possible association among household characteristics and FNS scores.

Household Dietary Diversity Score (HDDS) (Kennedy et al., 2011), generated from the household food security status and dietary intake data sets. The HHS was used to determine the level of hunger in a household. The HFIAS added additional insights of food (in) security, such as food quality, sufficiency, and psychological aspects (Coates et al., 2007; Maxwell et al., 2013) to measure the level of food insecurity in a household. In addition, HDDS was used to scout the adequacy of provided energy. Finally, the scores generated by each proxy were compared against standardized cut-off points of FAO and Food and Nutrition Technical Assistance Project (FANTA) (Coates et al., 2007; Ballard et al., 2011; Kennedy et al., 2011) to determine food security status of the sample household.

Household dietary pattern

After determining the household food (in) security status, we aimed to disclose if the foods consumed are diverse enough to satisfy the household nutrition security. That was done by recording the food consumption history of each household in three-time reference periods, i.e., 24 h, 7 days, and 4 weeks; and classify the food items into 12 food groups, i.e., cereals, white roots and tubers, vegetables, fruits, meat and poultry, eggs, fish and seafood, pulses/legumes/nuts, dairy products, oil and fat, sweets, and spices, condiments, and beverages (Swindale and Bilinsky, 2006).

Dietary adequacy

The nutrient/dietary adequacy to meet the minimum physiological requirements of the household, were determined applying indicators for food and nutrition adequacy to two sensitive groups: NBF children under 5 years and WRA, assumedly the most vulnerable groups (WHO, 2008; FAO and FHI 360, 2016). It was achieved using the Food Consumption Score (FCS) in reference period 7 days. For that, the food consumed was reclassified into nine food groups to build a score for each target group (WFP-VAM, 2009). The consumption frequency of each food group was weighted by the values given by the World Food Program (WFP) and summed up to provide individual FCS, which finally were used to determine the dietary adequacy using standardized cut-off points as poor, borderline and acceptable (WFP-VAM, 2009). Finally, the level of adequacy of three key nutrients, namely protein, vitamin A, and heme iron was analyzed (WFP-VAM, 2009, 2015). This process was carried out for two seasons to investigate the impact of the seasonal diet change on the dietary adequacy of the target groups.

Nutritional status

Nutritional status was assessed *via* z-score anthropometric measurements, that contrast individual performances against averages, were applied to the two sensitive groups. For the NBF under 5 years, the Multicentre Growth Reference Study (MGRS) (WHO, 2006) was followed to calculate the three *z*-score indicators, i.e., weight for height *z*-score (WHZ), weight for age *z*-score (WAZ), and height for age *z*-score (HAZ), which were later compared against the standard nutritional status cut-off points of WHO (WHO, 2006). Regarding WRA, the body mass index (BMI) was estimated and later contrasted against the combined four categories set by the WHO (1999) and Food and Nutrition Technical Assistance III Project (FANTA) (2016).

Statistical analyses

Statistical analyses included the estimation of descriptive statistics such as mean, median, and frequency of samples concerning relevant parameters of food and nutrition security. Variabilities and distributions among categories were tested using the parametric *F*-test. For the seasonal variation of scores, the paired *t*-test was applied. For children-women comparison, two-sample *t*-tests were employed.

Besides, a Spearman R non-parametric tool was used to detect the potential correlation between household characteristics and FNS scores. Before correlation analysis, all continuous variables of household characteristics were grouped into classes and became categorical variables to reduce error from the analysis of incompatible variables. All of statistical estimation and analysis were performed using Microsoft Excel Pus 2016, Minitab 17.1.0, STATISTICA 7.1., and ENA for SMART software.

Results

Socioeconomic profiling

The Yayu households' food and nutrition situations have a relationship with their socioeconomic and demographic characteristics. Out of the 140 sampled households, 88.5% had three to eight members with an average of 5.7 ± 2.2 members. 95.0% of the sampled households were male-headed, aging around 37.1 ± 11.3 years; 38.6% of these house heads achieved at least elementary school level (grade 1–6), but about 27.9% of the household heads illiterate. Eighty-four percent of the householders were native, while 15% were resettled from other regions. "Oromo" was the major ethnic group (75.5%) followed by Amhara (15.7%). Finally, 47.9% of the households were regarded as poor and 18.8% as rich (Table 1).

Food security status

Based on the estimated HHS, there was no hunger during the surplus season, and more than 83% of the households were also hunger-free in the shortage season. From the households detected as "hungry" (23), only two were severely affected. By adjusting the HHS results with the HFIAS questions, the proportion of food-secure households in the surplus season was revealed to be 70.7%, and in the shortage, season dropped to 18.5%. The mean HFIAS indices ranged between 1.6 ± 3.0 (surplus season) and 10.3 ± 6.2 (shortage season). Most households had a medium access to an optimum dietary energy provision in all seasons, i.e., 23.5% during the shortage and 16.4% during the surplus season. The average HDDS was 6.7 ± 1.2 (surplus season) and 6.4 ± 1.1 (shortage season) (Table 2).

The Spearman R correlation analysis was performed on the household attributes and the three food security status scores. "Wealth" is significantly correlated ($p < 0.001$) with all scores except for HHS and HDDS during the surplus season. The highest value obtained was for HFIAS ($r = -0.85$) and the lowest for HDDS ($r = 0.48$). "Family size" was highly significantly correlated with HFIAS in both seasons. "Head gender" is significantly ($p < 0.01$) correlated with HHS and HFIAS in shortage season. Unlike in PRFP, "settlement history" and "ethnicity" of the head has showed significant association with HFIAS ($r = 0.17$, $p < 0.05$) and HDDS ($r = -0.20$, $p < 0.05$) during shortage time, respectively. In contrast, a significant association of "educational level" was only recorded by PRFP

TABLE 1 Descriptive statistics and respective levels and codes of the socioeconomic and demographic attributes of sample households of Yayu.

Attributes	Levels/Classes	Code	Mean ± SD/*n* (%)	Levels/Classes	Code	Mean ± SD/*n* (%)
	Head's			**PRFP's**		
Gender	Male	1	133 (95)	Male	1	0 (0)
	Female	2	7 (5)	Female	2	140 (100)
Age in years (a)	a≤25	1	14 (10.0)	a≤20	1	19(13.6)
	25<a≤30	2	41 (29.3)	20<a≤25	2	45 (32.1)
	30<a≤40	3	46 (32.9)	25<a≤30	3	30 (21.4)
	40<a≤50	4	24 (17.1%)	30<a≤35	4	21 (15.0)
	50<a≤60	5	10 (7.1)	35<a≤40	5	16 (11.4)
	60<a	6	10 (3.6)	40<a	6	9 (6.4)
	Average		**37.1 ± 11.3**	**Average**		**29.0 ± 7.7**
Settlement history	Settled from another region	1	21 (15)	Settled from another region	1	19 (13.6)
	Moved within the region	2	1 (0.7)	Moved within the region	2	1 (0.7)
	Born in the current *woreda*	3	118 (84.2)	Born in the current *woreda*	3	120 (85.7)
Educational level	Not attended school	1	39 (27.9)	Not attended school	1	61 (43.6)
	Basic education	2	9 (6.4)	Basic education	2	2 (1.4)
	Elementary school, grade 1–6	3	54 (38.6)	Elementary school	3	47 (33.6)
	Junior school, grade 7–8	4	24 (17.1)	Junior school	4	15 (10.7)
	Secondary school, grade 9–10	5	12 (8.6)	Secondary school	5	10 (7.1)
	Above grade 10	6	2 (1.4)	Above grade 10	6	5 (3.6)
Ethnicity	Oromo	1	106 (75.7)	Oromo	1	111 (79.3)
	Amhara	2	22 (15.7)	Amhara	2	15 (10.7)
	Tigireway	3	9 (6.4)	Tigireway	3	7 (5.0)
	Other	4	3 (2.1)	Other	4	7 (5.0)
Religion	Orthodox	1	56 (40)	Orthodox	1	56 (40.0)
	Muslim	2	52 (37.1)	Muslim	2	52 (37.1)
	Protestant	3	32 (22.9)	Protestant	3	32 (22.9)
			Household's			
Family size (f)			f≤2		1	1 (0.7)
			2<f≤4		2	45 (32.1)
			4<f≤6		3	48 (34.3)
			6<f≤8		4	31 (22.1)
			8<f≤10		5	10 (7.1)
			10<f		6	5 (3.6)
			Average			**5.7 ± 2.2**
Wealth rank			Poor		1	66 (47.1)
			Medium		2	48 (34.3)
			Rich		3	26 (18.8)

and HDDS ($r = 0.26$, $p < 0.01$) in surplus season. Religion has not shown significant association with all of the food security status scores (Table 3).

Dietary patterns

Considering three-time references (24 h, 7 days, and 4 weeks), and the surplus and shortage seasons, it was found that from the 12 food groups considered, cereals, oil and fats, vegetables, and spices, condiments and beverages, were the food groups consumed by more than 98% of the households. White root and tubers, and dairy products showed higher consumption frequencies during the shortage season, while the remaining food groups showed higher consumption frequencies during the surplus season. Across the three time preferences, only the food group "fish" is consistently absent and considered exotic (Figure 3).

TABLE 2 Average, standard deviation, count, and proportion of three food security scores (HHS, Household Hunger Scale; HFIAS, Household Food Insecurity Access Scale; HDDS, Household Dietary Diversity Score) across seasons in Yayu.

Score	Category	Surplus season		Shortage season	
		Mean ± SD	*n* (%)	Mean ± SD	*n* (%)
HHS	Little to no hunger	0.01 ± 0.1	140 (100.0)	0.3 ± 0.4^{C}	117 (83.6)
	Moderate hunger	N.A	0 (0.0)	3.2 ± 1.0^{B}	21 (15.0)
	Severe hunger	N.A	0 (0.0)	6.5 ± 0.7^{A}	2 (1.4)
	Category variation	N.A		$p < 0.01$	
	Average/total	0.01 ± 0.1	140 (100.0)	0.8 ± 1.4	140 (100.0)
	Seasonal variation	$p < 0.01$			
HFIAS	Food secure	0.2 ± 0.4^{C}	99 (70.7)	0.0 ± 0.0^{C}	26 (18.6)
	Mildly food insecure	4.3 ± 1.7^{B}	39 (27.9)	6.5 ± 0.7^{B}	12 (8.6)
	Moderately food insecure	N.A	0 (0.0)	12.9 ± 2.4^{A}	48 (34.3)
	Severely food insecure	19.0 ± 0.00^{A}	2 (1.4)	14.7 ± 4.3^{A}	54 (38.6)
	Category variation	$p < 0.01$		$p < 0.01$	
	Average/total	1.6 ± 3.0	140 (100.0)	10.3 ± 6.2	140 (100.0)
	Seasonal variation	$p<0.01$			
HDDS	Low	4.9 ± 0.2^{C}	23 (16.4)	4.9 ± 0.3^{C}	33 (23.6)
	Medium	6.4 ± 0.5^{B}	78 (55.7)	6.5 ± 0.5^{B}	86 (61.4)
	High	8.2 ± 0.5^{A}	39 (27.9)	8.2 ± 0.4^{A}	21 (15.0)
	Category variation	$p < 0.01$		$p < 0.01$	
	Average/total	6.7 ± 1.2	140 (100.0)	6.4 ± 1.1	140 (100.0)
	Seasonal variation	$p < 0.012$			

Categories values with same superscript do not differ significantly at $\alpha = 0.05$.
N.A, statistical test not applicable.

Dietary adequacy

According to the FCS cut-off points, there was no "poor" food consumption. More than 87% of the children and women fell in the category "acceptable." The mean of the 7-day weighted FCS for NBF children under 5 years was 53.5 ± 14.2 and 56.3 ± 18.1, and for WRA 52.4 ± 1.1 and 54.6 ± 15.7, for the surplus and shortage season, respectively. The means weighted FCS of both target groups were higher in the shortage season ($p < 0.05$) (Table 4). Apart from this, there was no significant difference among target groups.

A further assessment of key micronutrients intake (vitamin A, protein and heme iron), shows that 6.4% and 17.9% of NBF children under 5 years and WRA, respectively, did not consume any vitamin-A-rich food group during the surplus period. No seasonal variation was observed regarding the consumption of protein-rich foods among children, but 3.6% of women showed no consumption at all of protein during the lean season. The most critical result was observed regarding foods rich in heme iron, as more than 50% of both target groups lacked foods that contain it; even worse, in the surplus season, it increased up to 87.9% for the shortage season (Figure 4).

Correlation analyses shows that "head age," "family size," and "wealth rank" are significantly correlated with the FCS for both target groups in both seasons with their highest score of 0.21 ($p < 0.05$), 0.31 ($p < 0.001$), and 0.77 ($p < 0.001$), respectively. "Settlement history" and "ethnicity" of the head and PRFP have shown a highly significant correlation with FCS of both targets during the shortage season with r ranging from 0.22 to 0.26 (Table 5).

Nutritional status

NBF children under 5 years

The distribution of WHZ the scores of NBF children under 5 years show that 2.9 and 3.9% of the children were wasted in the surplus and shortage seasons, respectively. The comparison of the WAZ scores against standard cut-off values (WHO, 2006) reveals that about 5 and 10% of the children were underweight, out of which 1.2 and 2.4% were severely underweight during the surplus and shortage seasons, respectively. The distribution of the HAZ shows the prevalence of stunting 17 and 38% in the surplus and shortage seasons respectively, of which 1.4 and 9.2% happen to be severely stunted during the surplus and shortage seasons, respectively (Table 6).

TABLE 3 Spearman R correlation coefficient among food security scores (HHS, Household Hunger Scale; HFIAS, Household Food Insecurity Access Scale; HDDS, Household Dietary Diversity Score; please note that the third differs from the first two in direction) and characteristics of households in surplus and shortage seasons in Yayu.

Household characteristics	HHS		HFIAS		HDDS	
	Surplus	Shortage	Surplus	Shortage	Surplus	Shortage
Head gender[β]	−0.03	0.23**	0.18*	0.22**	0.15	−0.04
Head age	−0.04	−0.09	−0.24**	−0.27**	0.05	0.19*
Head settlement history[β]	0.05	0.12	0.10	0.17*	0.10	−0.13
Head educational level	0.08	0.04	0.06	0.14	0.11	0.03
Head ethnicity[β]	−0.07	−0.15	−0.15	−0.14	−0.02	0.20*
Head religion[β]	0.11	0.04	0.11	0.00	0.02	−0.07
PRFP age	−0.08	0.07	−0.08	−0.14	0.11	0.01
PRFP settlement history[β]	0.05	0.10	−0.02	0.03	0.06	−0.02
PRFP educational level	0.10	0.06	0.12	0.13	0.26**	−0.12
PRFP ethnicity[β]	−0.06	−0.09	−0.02	−0.04	−0.03	0.09
PRFP religion[β]	0.11	0.04	0.11	0.00	0.02	−0.07
Family size	−0.14	−0.02	−0.22**	−0.26**	0.02	0.15
Wealth rank	−0.12	−0.57***	−0.60***	−0.85***	0.15	0.48***

PRFP, person responsible for food preparation; WRA, woman of reproductive age; NBF, non-breast feeding.
*Significant at $p < 0.05$.
**Significant at $p < 0.01$.
***Significant at $p < 0.001$.
[β] Attributes with nominal values.
N.B., negative "r" values do not show the direction of correlation except those variable with nominal value; wealth ranks 1 = poor and 3 = rich.

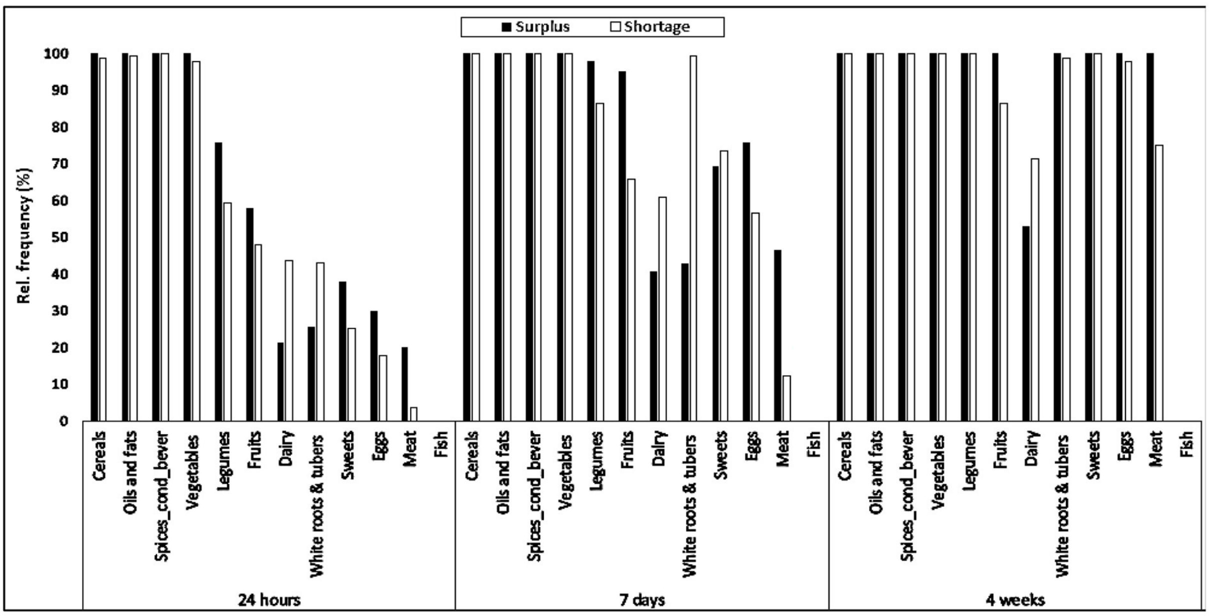

FIGURE 3
Relative consumption frequency of 12-food groups during two seasons and three reference periods of households in Yayu.

Women of reproductive age

The distribution of the BMI of WRA showed that 10.9% of the assessed individuals were malnourished in the surplus season and 13.6% in the shortage season, while 87.6 and 83.4% fell between the normal ranges in the surplus and shortage seasons, respectively ($p < 0.01$). Accordingly, tests of variation across

TABLE 4 Weekly Food Consumption Score of target groups across categories and seasons in Yayu.

Target groups	Category	Surplus season		Shortage season	
		Mean ± SD	n (%)	Mean ± SD	n (%)
NBF children < 5 yrs.	Poor	-	-	-	-
	Borderline	31.6 ± 2.6[B]	17 (12.4)	30.2 ± 3.3[B]	15 (10.7)
	Acceptable	56.9 ± 12.4[A]	123 (87.6)	59.5 ± 16.6[A]	125 (89.3)
	Category variation	$p < 0.01$		$p < 0.01$	
	Average/total	53.5 ± 14.2	140 (100.0)	56.3 ± 18.1	140 (100.0)
	Season variation	$p = 0.018$			
WRA	Poor	-	-	-	-
	Borderline	30.2 ± 3.6[B]	13 (9.2)	30.2 ± 3.2[B]	15 (10.7)
	Acceptable	54.6 ± 12.5[A]	127 (90.7)	57.5 ± 13.9[A]	125 (89.3)
	Category variation	$p < 0.01$		$p < 0.01$	
	Average/total	52.4 ± 13.4	140 (100.0)	54.6 ± 15.7	140 (100.0)
	Season variation	$p = 0.046$			
Target group variation		$p = 0.686$		$p = 0.791$	

Categories values with the same superscript do not differ significantly at $\alpha = 0.05$.
WRA, woman of reproductive age; NBF, non-breast feeding.

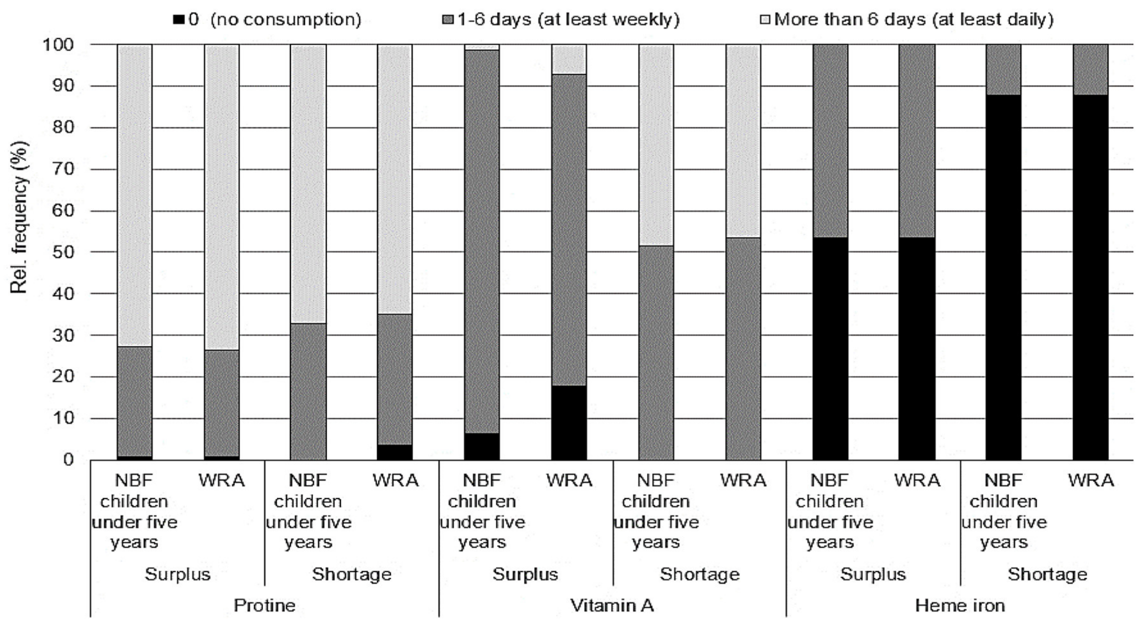

FIGURE 4
Weekly consumption frequency of target groups of food groups rich in key micronutrients during surplus and shortage seasons in Yayu (WRA, woman of reproductive age; NBF, non-breast feeding).

the malnutrition categories and seasons revealed being highly significant ($p < 0.01$) (Table 7).

The Spearman R correlation analysis shows that the all anthropometric indicators of NBF children under 5 years (HAZ, WAZ, and WHZ) in both seasons were positively associated with the "wealth rank" and "family size" of the households with a minimum and maximum value of $r = 0.20$ ($p < 0.05$) and 0.46 ($p < 0.001$), respectively. Compared to the z-scores, "Head age" is correlated with two anthropometric indicators of NBF children under 5 years (HAZ and WAZ)

TABLE 5 Spearman R correlation coefficients among dietary adequacy scores of (FCS, Food Consumption Score) of the two target groups and characteristics of households in surplus and shortage seasons in Yayu.

Household characteristic	NBF children under 5 yrs.		WRA	
	Surplus	Shortage	Surplus	Shortage
Head gender[β]	−0.14	−0.04	−0.14	−0.05
Head age	0.21*	0.21*	0.20*	0.18*
Head settlement history	−0.16	−0.26**	−0.15	−0.26**
Head educational status	−0.05	−0.11	−0.02	−0.08
Head ethnicity[β]	0.16	0.22**	0.17*	0.22**
Head religion[β]	−0.06	−0.17*	−0.09	−0.15
PRPF age	0.12	0.17*	0.09	0.15
PRPF settlement history[β]	−0.04	−0.24**	−0.03	−0.24**
PRPF educational status	−0.06	−0.10	−0.05	−0.07
PRPF ethnicity[β]	0.09	0.25**	0.11	0.25**
PRPF religion[β]	−0.06	−0.17*	−0.09	−0.15
Family size	0.31***	0.20*	0.28***	0.18*
Wealth rank	0.77***	0.68***	0.77***	0.66***

PRPF, person responsible for preparing food; WRA, woman of reproductive age; NBF, non-breast feeding.
*Significant at $p < 0.05$.
**Significant at $p < 0.01$.
***Significant at $p < 0.001$.
[β] Attributes with nominal values.
N.B., negative "r" values do not show the direction of correlation except those variables with nominal value; wealth ranks 1 = poor and 3 = rich.

TABLE 6 Prevalence of malnutrition of children under 5 years during surplus and shortage season in Yayu.

Malnutrition category	Prevalence of malnutrition *n* (%) (C.I. 95%)	
	Surplus season	Shortage season
Wasted	4 (2.9%) (0.1–5.6)	3 (3.9%) (−0.4–8.3)
Moderate	3 (2.1%) (−0.3–4.5)	3 (3.9%) (−0.4–8.3)
Severe	1 (0.7%) (−0.7–2.1)	0 (0.0 %) (0.0–0.0)
Underweight	7 (5.0 %) (1.4–8.6)	8 (10%) (3.6–17.4)
Moderate	5 (3.6%) (0.5–6.6)	6 (7.9%) (1.8–14.0)
Severe	2 (1.4%) (−0.5–3.4)	2 (2.6%) (−1.0–6.2)
Stunted	25 (17.9%) (11.5–24.2)	29 (38.2%) (27.2–49.1)
Moderate	23 (16.4%) (10.3–22.6)	22 (28.9%) (18.8–39.1)
Severe	2 (1.4%) (−0.5–3.4)	7 (9.2%) (2.7–15.7)

of both seasons were 0.24 ($p < 0.01$) scored as the weakest. Similarly, the educational level of the head and PRFP were positively correlated with the same indicators at least in one of the two seasons at $\alpha = 95\%$ (Table 8). Whereas, no household characteristic showed a significant association with the HAZ indicator was also positively correlated with the anthropometric indicators of WRA in both seasons (Table 8).

Discussion

Food security status

Yayu household communities do not suffer hunger during the surplus season. This partly agrees with the annual food security outlook reports of the Famine Early Warning Systems Network from 2005 onwards, which labels Yayu as a hunger-free zone (FEWS NET, 2002, 2004, 2005, 2009, 2011, 2013, 2015, 2017). However, about 16% of the households were affected by hunger during the shortage season, out of which 1.4% fell in the "severely hungry" category. Based on the basic household characteristic of the affected households this might be caused either by big family size or by the insufficient size of farmland of the households, this agrees with a study conducted on smallholder farmers in Zimbabwe (Rubhara et al., 2020). These findings suggest that the seasonal fluctuation may have been ignored in previous assessments. Nevertheless, the majority of the Yayu smallholder farm households can still be regarded as hunger-free.

Other parts of this study Jemal et al. (2018) have linked the food security and nutritional status of the householders of Yayu, to their practice of three dominant land uses: homegarden, coffee agroforestry, and farmland. Households, mostly migrants, who focus on coffee agroforestry may do well in terms of income generation, but are the least food secure. In the data presented

TABLE 7 Mean, proportion (%) and test of variation of BMI-based nutrition category of women of reproductive age during surplus and shortage seasons in Yayu.

Malnutrition category	Surplus season		Shortage season	
	Mean ± SD	*n* (%)	Mean ± SD	*n* (%)
Malnourished	17.8 ± 0.6^{C}	14 (10.9)	17.7 ± 0.8^{C}	19 (13.6)
Severe	N.A	0 (0.0)	15.8 ± 0.1C	2 (1.7)
Moderate	16.5 ± 0.1^{C}	2 (1.6)	N.A	0 (0.0)
Mild	18.0 ± 0.4^{C}	12 (9.3)	18.0 ± 0.4C	14 (11.6)
Normal	20.8 ± 1.4^{B}	113 (87.6)	20.9 ± 1.5^{B}	101 (83.4)
Overweight	25.2 ± 0.2^{A}	2 (1.6)	26.1 ± 2.0^{A}	4 (3.3)
Obese	N.A	0 (0.0)	N.A	0 (0.0)
Category variation	$p < 0.01$		$p < 0.01$	
Average/Total	20.6 ± 1.7	129 (100.0)	20.6 ± 2.1	121 (100.0)
Season variation	$p < 0.01$			

Categories values with same letter do not differ significantly at α = 0.05.
N.A, statistical test not applicable.

TABLE 8 Spearman R correlation coefficients among nutritional status scores [weight for height *z*-score (WHZ), weight for age *z*-score (WAZ), and height for age *z*-score (HAZ), and body mass index (BMI) target children and women, respectively] and characteristics of households in surplus and shortage seasons in Yayu.

Household characteristic	NBF children under 5 yrs.						WRA	
	HAZ		WHZ		WAZ		BMI	
	Surplus	Shortage	Surplus	Shortage	Surplus	Shortage	Surplus	Shortage
Head gender$^{\beta}$	−0.15	−0.08	−0.13	−0.08	−0.13	−0.14	0.00	−0.08
Head age	0.27**	0.36***	0.24**	0.39***	0.15	0.12	−0.01	0.02
Head settlement history$^{\beta}$	−0.14	−0.08	−0.06	−0.07	−0.12	−0.11	0.09	−0.05
Head educational status	−0.17*	−0.19	−0.14	−0.25*	−0.08	−0.06	−0.03	−0.08
Head ethnicity$^{\beta}$	0.05	0.00	0.02	−0.04	0.04	0.07	−0.07	0.04
Head religion$^{\beta}$	−0.15	−0.15	−0.07	−0.13	−0.11	−0.20	0.08	0.05
PRPF age	0.12	0.18	0.10	0.23*	0.06	0.04	−0.03	0.03
PRPF settlement history$^{\beta}$	−0.09	0.04	−0.08	−0.07	−0.05	0.06	0.15	0.10
PRPF educational status	−0.14	−0.28*	−0.21*	−0.32*	−0.02	−0.05	−0.08	−0.08
PRPF ethnicity$^{\beta}$	0.04	−0.09	0.01	−0.03	−0.01	−0.11	−0.16	−0.03
PRPF religion$^{\beta}$	−0.15	−0.15	−0.07	−0.13	−0.11	−0.20	0.08	0.05
Family size	0.28***	0.35**	0.20*	0.23*	0.20*	0.30**	−0.01	0.08
Wealth rank	0.38***	0.46***	0.33***	0.38***	0.25**	0.30**	−0.02	0.17

PRPF, person responsible for preparing food; WRA, woman of reproductive age; NBF, non–breast feeding.
*Significant at p < 0.05.
**Significant at p < 0.01.
***Significant at p < 0.001.
$^{\beta}$Attributes with nominal values.
N.B., negative "r" values do not show the direction of correlation except those variables with nominal value; wealth ranks 1 = poor and 3 = rich.

here, however, settlement history does not have a statistically significant effect on the food security indicators.

Concerning HFIAS, average values of the surplus (1.6 ± 3.0) and the shortage season (10.3 ± 6.2) of Yayu were lower and higher, respectively, than the national average values of 6.7 ± 6.7 reported by Ali et al. (2013). In Sidama, southern Ethiopia, Joray et al. (2011) observed HFIAS values of 3.6 and 8.8 for the surplus and shortage season, respectively. In the same line, Gebreyesus et al. (2015) reported a mean HFIAS of 6.4 for the Gurahgae zone, also labeled as food-secure. As shown, during the surplus season Yayu had higher food security ratios than other food-secure areas of the country, and during the shortage season, it was also slightly higher than in those areas. This might be due to the growing dependency on marketed food during the shortage season.

Another aspect of the food security status relates to the economic capability of the households to acquire a variety of food, an issue tackled by the HDDS. The average HDDS of Yayu was 6.7 ± 1.2 and 6.4 ± 1.1 for the surplus and shortage season, respectively. The mean value of the surplus season was similar to the national average (6.7) but higher than the one of the shortage season (5.9) (Hirvonen et al., 2015). Also, the Welfare Monitoring Survey of Ethiopia Workicho et al. (2016) reported a mean HDDS value of 5.0 ± 1.9, which is lower than the obtained values for both seasons in Yayu. In similar reports Coates and Galante (2014) and Gebreyesus et al. (2015), found similar seasonal fluctuations for the HDDS.

The association observed between the households' food security and their wealth agree with a study performed in the Sidama communities in southern Ethiopia (Regassa and Stoecker, 2011). Noticeably, the wealth rank estimation is based on the landholding size, which is directly associated with the amount of food (produced) and cash (generated) by a given household can obtain (Yayu, Hurumu, Doreni, and Chora *Woreda* administration offices).

Dietary pattern

The comparison of the dietary patterns of smallholder farming households in Yayu with the findings of Coates and Galante (2014) and Workicho et al. (2016) at national level are presented in Table 9. The predominance of cereal-based diets, and the consumption values equivalent to the national average values are observed; the same applies to tubers. However, tubers consumption doubles during the shortage season, by their coincident increased availability and scarcity of other staples. This is why white tubers are often labeled as shortage time foods.

Concerning other food groups, their weekly consumption values in Yayu were higher than national averages, even during the shortage season, with the exception of meat where consumption is particularly low in the shortage season, and fish that is not consumed at all, issue confirmed by Workicho et al. (2016). In the present study, the share of legumes consumption was 97.7 and 86.4% during the surplus and shortage season, respectively, which are higher than the values for all Ethiopian regions studied by Coates and Galante (2014).

Dietary adequacy

Compared with the national average reported by Central Statistical Agency (CSA), and World Food Programme (WFP) (2014) where 10% of the population exhibits a "poor" dietary adequacy, the households of Yayu perform relatively well. No "poor" dietary adequacy was identified in either season, as Yayu people uses different leaves, roots and tuber crops to cope with seasonal shortages. However, 10.1% of the target children and 9.2% of the women exhibit a borderline nutritional adequacy performance, which suggests a risk of nutrition insecurity in a considerable share of the households.

The study detected non-significant variations in the dietary adequacy by target groups across seasons. In contrast, Hirvonen et al. (2015) reported a significant seasonal variation in the overall dietary intake of 27,835 households in all regions of Ethiopia. On the weekly consumption of key nutrients, heme iron is the most critical nutrient, as its consumption was notably low in both target groups. The situation aggravates in the shortage season, opening the possibility of a chronic deficiency. This problem is not exclusive to Yayu, as it is reported countrywide (Central Statistical Agency (CSA), and World Food Programme (WFP), 2014). Also the interesting finding is the decrease in the consumption of vitamin-A-rich foods in the surplus season, likely due to the reduction in the consumption of dark green vegetables, which in Yayu are considered as "shortage season" food. In addition, the consumption of dairy products was higher in the shortage seasons, concurrent with the higher availability of forage at the beginning of the rainy season.

A correlation between the weekly and daily dietary diversity intake scores and the settlement history and ethnicity of the households was identified. As both are assumedly proxies of knowledge of the type, importance, and management of the flora, which implies that the indigenous knowledge has a positive contribution to the dietary habits of households. This situation should be emphasized in further studies, which should consider the interfaces between social, cultural, nutritional, and ecological parameters as entry points to address FNS.

Nutritional status

In the same line, the anthropometric indicators of NBF children under 5 years confirmed that part of the community is not nutritionally secure, especially during the shortage season, when the lowest value was recorded: 3.9% of wasted children, which fall in the "low prevalence" category of the WHO cut-off points (WHO, 1995). However, these values are still lower than the Ethiopian national average (7–9%). On the other hand, the prevalence of stunting (38.2%) was equivalent to the national levels (36.8–38.4%) (Central Statistical Agency International ICF, 2016; Ethiopian Public Health Institute ICF, 2019) and regarded as "high prevalence" (30–39%) (WHO, 1995) (Table 10).

The distribution of anthropometric *z*-scores for the two seasons compared with the WHO standards, shows that the weight for age and the height for age *z*-scores distribution of the NBF children under 5 years in both seasons, were skewed to the left; and more pronounced during the shortage season

TABLE 9 Comparison of weekly consumption trend of food groups in all regions in Ethiopia against Yayu values.

Food group	National and regional level		Yayu	
	All regions[a]	All regions except three pastoral regions[b]	Surplus season	Shortage season
Cereals	95.3%	95.1–99.8%	100.0%	100.0%
White roots and tubers	44.0%	20.8–65.2%	42.9%	99.3%
Vegetables	48.6%	78.9–93.8%	100.0%	100.0%
Fruits	14.9%	10.6–54.4%	95.0%	65.7%
Meat and poultry	26.2%	22.7–70.8%	46.4%	12.1%
Eggs	11.3%	4.9–50.5%	75.7%	56.4%
Fish and seafood	0.9%	0.1–2.6%	0.0%	0.0%
Pulses/legumes/nuts	66.4%	71.9–92.8%	97.9%	86.4%
Dairy products	38.3%	27.2–62.3%	40.7%	60.7%
Oil and fat	72.9%	69.3–99.3%	100.0%	100.0%
Sweets	32.1%	28.5–84.2%	69.3%	73.6%
Spices, condiments and beverages	93.2%	N.A	100.0%	100.0%

[a] Coates and Galante (2014).
[b] Workicho et al. (2016).

TABLE 10 Prevalence of wasted, underweight and stunted NBF children under 5 years (national level, west Gojam zone, and Yayu).

Prevalence (%)	National			West Gojam	Yayu	
	2011[a]	2016[b]	2019[d]	2009[c]	Surplus	Shortage
Wasting	9.7%	9.9%	7.0%	14.8%	2.9%	3.9%
Underweight	28.7%	23.6%	21.3%	49.2%	5.0%	10.0%
Stunting	44.4%	38.4%	36.8%	43.2%	17.9%	38.2%

[a] ICF International (2012).
[b] Central Statistical Agency International ICF (2016).
[c] Teshome et al. (2009).
[d] Ethiopian Public Health Institute ICF (2019).

(Figures 5B,C). In contrast, the weight to height distribution shows a good fit with WHO standards (Figure 5A).

In the case of WRA, the anthropometric indicators show that 8.6% of them in Yayu were malnourished or moderately/severely thin. Still, the value is lower than the national value (27%) (ICF International, 2012). But these numbers increased during the shortage season to 13.6%, which WHO defines as a "poor situation," taken as a warning and suggests the monitoring of the community (WHO, 1995).

Conclusion

The findings indicate that smallholder farming communities of Yayu can be mostly considered hunger-free. Referring to the HFIAS-based food and nutrition security assessment, some households face moderate to severe food insecurity, which relates to their limited access to food. However, the area provides sufficient calories to the majority of households (>95%) and energy-rich staples all year long. Concerning the adequacy of consumed nutrients, the majority of the households surpasses the minimum consumption threshold.

The consumption of protein is common. The dietary diversity increases during the shortage season regardless of the amount of food available, due to the inclusion of milk and shortage-time food in the diets. The consumption of vitamin-A peaks in the shortage season, as people eat more dark green vegetables and dairy products but tend to attach to cereal-dominated diets during the surplus season. However, a chronic iron deficiency is possible due to the very low consumption of heme-iron-rich foods, especially during the shortage season. Alternatively, it was recoded that the existence of plant species rich in these scarce nutrients, but are generally underutilized or even neglected (Callo-Concha et al., 2019).

The observed levels of wasting, underweight and stunting in NBF children under 5 years, and malnourishment in WRA, suggest the existence of food and nutrition insecurity in few households. Food and nutrition security requires the availability of affordable quality food for a healthy life for all people at all times. The findings of the present study indicate seasonal

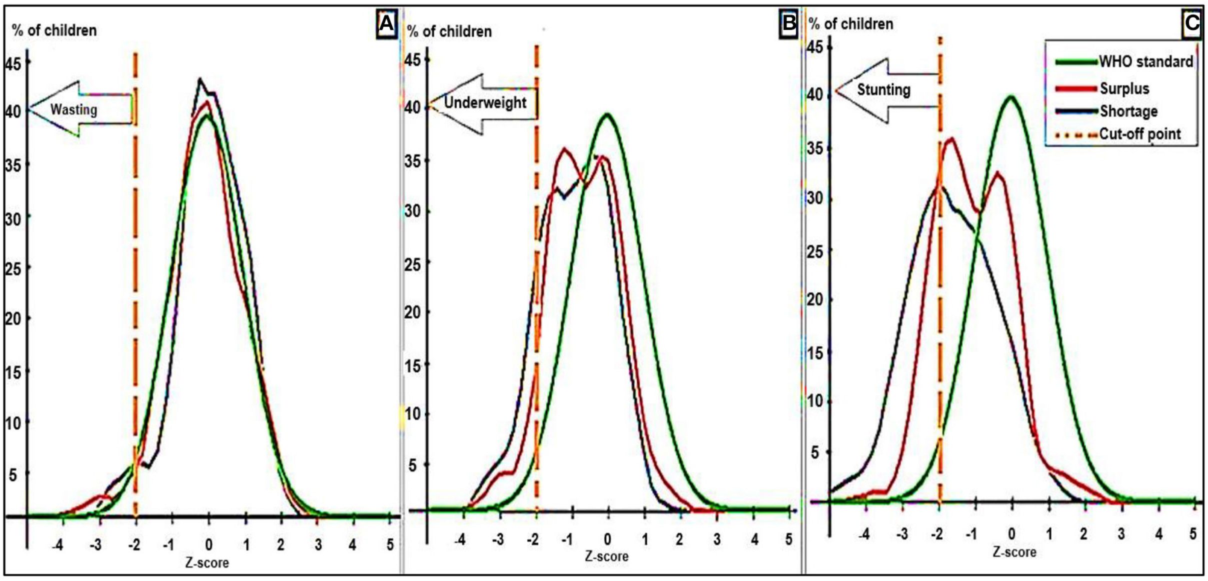

FIGURE 5
Distribution of anthropometric indicators of NBF children under 5 years in Yayu compared to global WHO references across seasons. **(A)** Weight for height. **(B)** Weight for age. **(C)** Height for age.

scarcity and qualitative deficiencies in the food consumed by households. Thus, Yayu cannot be considered fully food secure, though the situation is better than in most parts of the country. In general, a mere consideration of cash-crop growing communities (based on their income status) as food secure, is proved no to be a viable but a misleading approach. At least in the case of Yayu.

Further studies on seasonal nutritional deficits, through assessing available resources, utilization trends, farming systems, and related factors are recommended. Besides, as this study is based on a "proxy approach" to determine the food and nutritional security, which has intrinsic limitations, direct and more accurate methods such as blood analyses would provide more precise information on people's food and nutritional security.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving human participants were reviewed and approved by Ethical Approval Team of Center for Development Research (ZEF), University of Bonn, Genscheralle 3, 53113 Bonn, Germany. Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin.

Author contributions

OJ, DC-C, and MN contributed to conception, design of the study, and wrote sections of the manuscript. OJ organized the database, performed the statistical analysis, and wrote the first draft of the manuscript. All authors contributed to manuscript revision, read, and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Impact of the Productive SafetyNet Program on the minimum acceptable diet in the rural community of South Gondar Zone, Northwest Ethiopia

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Background: Even though numerous factors contribute to undernutrition, it can happen immediately due to poor intake and illness. A minimum acceptable diet is one of the proxy measures for adequate consumption, which is an impact indicator for the Productive SafetyNet Program (PSNP). As a result, this study aimed to assess the impact of PSNP on the minimum acceptable diet among rural infants in the South Gondar Zone, Northwest Ethiopia.

Methods: A community-based cross-sectional study design was employed in the selected woredas (districts) of South Gondar Zone, Northwest Ethiopia, from 1 December 2017 to 30 January 2017. A total of 442 participants' data were collected during this time period through interviews with their mothers or caregivers. A multistage sampling technique was employed to select study subjects and interviewees using a structured questionnaire. Stata version 16 (MP) was employed to carry out a statistical analysis. A binary logistic regression model was employed to identify significant variables. The statistical significance was declared at a *p*-value of more than 0.05.

Results: The highest proportion of adequate diet diversity scores (261 [59.05%]) was from households who graduated (not part of it) from PSNPs. In this study, the magnitude of adequate dietary diversity, meal frequency, and minimum acceptable diet was 79.86, 82.58, and 66.52%, respectively. Marital status (AOR = 3.98, 95% CI: 1.39, 11.40), child age (AOR = 2.82, 95% CI: 1.78, 4.47), the educational status of the father (AOR = 0.56, 95% CI: 0.35, 0.89), the wealth index (AOR = 0.27, 95% CI: 0.12, 0.64), and the place of delivery (AOR = 3.14, 95% CI: 1.47, 6.73) were significant predictors for minimum acceptable diet uptake by children.

Conclusion: In this study, two-thirds of the infants had/received a minimum acceptable diet. Furthermore, infants from households with Productive SafetyNet users had a low minimum acceptable diet. Marital status, the educational status of the father, child age, the wealth index, and the place of delivery were associated factors with having an adequate intake of minimum acceptable diet by the children. Therefore, efforts to address sociodemographic and child-related factors during routine care are crucial.

KEYWORDS

impact, Productive SafetyNet program, minimum acceptable diet, children, Ethiopia

Background

Even though Ethiopia has achieved success in various areas related to the millennium development goals (Horton and Lo, 2013), it currently faces significant challenges with regard to poverty and food insecurity due to high population growth (World Bank, 2015) and poor economic growth (Alderman, 2010; IFAD, 2016). Due to chronic food insecurity and low agricultural productivity, the Productive SafetyNet Program (PSNP) was implemented in Ethiopia in 2005 to tackle this problem. After 4 years, PSNP+ was introduced to include additional small income-generating activities among households to increase household income (Devereux et al., 2006; Gilligan et al., 2009; Berhane et al., 2012).

Despite the implementation of various interventions, food insecurity and hunger continue to be rampant and critical issues in Ethiopia, which have a significant impact on children's overall health [Devereux, 2000; CSA, 2011, 2014; Central Statistical Agency (Ethiopia) ICF International, 2016]. One of the main contributing factors to these issues is the inadequate intake of a variety of foods due to insufficient quantities and frequencies, particularly in the Amhara regional state [Central Statistical Agency (Ethiopia) ICF International, 2011, 2014]. Overall, food insecurity has an impact on educational attainment and attendance in Ethiopia (Belachew et al., 2011). The ultimate goal of PNSP is to ensure households build on-farm and off-farm activities to have a variety of procurement strategies for food and cash (Drinkwater and McEwan, 1992).

Livelihoods will be secured when households have secure ownership or access to resources and income-earning activities. It helps to reserve and build an asset, offset risks, ease shocks, and meet contingencies (Chambers, 1989; Frankenberger and McCaston, 1998) to mitigate the vulnerability risk of a household to income, food, health, and nutritional insecurity, which directly or indirectly affect the consumption behaviors of the families.

Abbreviations: AOR, adjusted odds ratio; COR, crude odds ratio; HEWs, health extension workers; MAD, minimum acceptable diet; MDDS, minimum dietary diversity score; MMF, minimum meal frequency; PSNP, Productive SafetyNet program; SD, standard deviation; WEPLAUO: Libo Kemekem Word Environmental Protection, Land Administration; SWEPLAUO: Simada Worda Environmental Protection, Land Administration and Use Office; WHO, World Health Organization.

The Phase 4 PSNPs were launched in Ethiopia to achieve the goal of "enhancing resilience to shocks and livelihoods, improving food security and nutrition, for rural households vulnerable to food insecurity." Thus, the PSNP's contribution to this goal was assessed through program impact assessments by using the percentage of infants aged 6 to 23 months who receive a minimum acceptable diet, household dietary diversity, the average value of asset holdings, and the number of different income sources. For this study, we intended to use the minimum acceptable diet among infants aged 6–23 months as an indicator of the impact assessment (MoALR, 2014).

In Ethiopia, the magnitude of the Minimum Acceptable Diet (MAD) is the lowest, which ranges from 4.2 to 13.3% (Abeshu et al., 2016; Gizaw and Tesfaye, 2019; Mulat et al., 2019; Tassew et al., 2019). The levels of the Minimum Dietary Diversity Score (MDDS) and Minimum Meal Frequency (MMF) are 45 and 33%, respectively, which are high as compared to the findings of the study in North Showa (Gizaw and Tesfaye, 2019). This might be due to household food insecurity, which mainly affects low-income populations, particularly in developing economies undergoing the demographic transition; hence, low socioeconomic status leads to poor diet, food insecurity, and ill health among infants (FAO, 2003; Popkin, 2004; Conforti NWCCNTP, 2014). In addition, demographic and other maternal and child-related predictors affect children's MAD through dietary diversity and meal frequency (Laraia et al., 2006). As mentioned above, even though there are studies on the general population and each independent indicator of MAD, there are none on PSNP beneficiaries on this topic. Thus, this study aimed to assess the impact of PSNP on a minimum acceptable diet of infants aged 6–23 months in the selected rural community of South Gondar Zone, Northwest Ethiopia.

Materials and methods

Study design, period, and setting

The data were collected through a community-based cross-sectional study design from 1 December 2017 to 30 January 2017. Then, we compared these data based on the household's Productive SafetyNet enrollment status.

If the number of woredas (districts) in South Gondar with PSNP was five (Libo Kemkem, Simada, Lay Gayint, Tach Gayint, and Ebnat), the data were collected at the rural kebeles of Libo Kemkem and Simada woredas in South Gondar Zone, Northwest Ethiopia. The topography of these woredas (districts) belongs to highlands with plain and mountainous features, and both woredas (districts) are found at 1,800 m above the sea level (SWEPLAUO, 2020; WEPLAUO, 2020).

If these people are chronically food insecure, agricultural cultivation includes maize, barley, and millet, which are the main food crops, while rice and chickpeas are the main cash crops. The total number of households with the Productive SafetyNet program in Libo Kemekem and Simada woredas was more than 9,000, participating either in public works or direct support. At the time of data collection, nearly 4,500 infants aged 6–23 months were found in these woredas.

Sample size determination

The first study included a total of 769 participants. Of these, data from 442 infants aged 6–23 months were retrieved for this study after removing incomplete data and data from infants under the age of 23 months.

Eligibility criteria

We included data of all children aged 6 to 23 months of complete dietary diversity and meal frequency variables; if either of them were incomplete, we excluded them from this study.

Patient and public involvement

During this study, no patients or members of the general public were involved in the development of the research question, data collection, or analysis.

Sampling procedure

During the primary data collection, a multistage sampling method was employed by allocating the calculated sample size to each designated Kebeles of selected woredas, and the data were collected at the household level. Then, the refined data were analyzed.

Data collection methods and tools

During the primary data collection phase, the pretested Amharic version questionnaire was employed after being translated from the English language, which consists of socioeconomic and consumption-related variables. The dietary intake and minimum meal frequency data were collected using seven food groups through a 24-h dietary recall. Ten BSc nurse enumerators collected the data.

Data quality

Prior to the original data collection, a pretest was conducted on 5% of the total sample size. The data collectors received 1 day of training with a pretest, and the questionnaire was administered in Amharic (the local language). During the primary data collection period, regular communication was maintained to discuss the progress and any issues that arose. The collected data were checked for completeness and consistency by the investigators and supervisors. All data collectors were recruited outside the study area to minimize bias.

Term definitions

- **Households with PNSPs**: These households are identified as chronically food insecure and are currently a part of cash transfer or asset-building programs.
- **Households without PNSPs:** These households are not identified as chronically food insecure because they graduated from PNSPs and are not currently part of cash transfer or asset-building programs.
- **Kebele:** It is the smallest administrative division or village in Ethiopia.
- **Minimum dietary diversity:** It is the proportion of infants aged 6–23 months who received ≥4 food groups from the seven through a 24-h dietary recall; it is categorized as inadequate if dietary diversity has ≤4 food groups and good if the individual dietary diversity has ≥5 food groups according to FAO.
- **Minimum meal frequency**: It is the proportion of breastfed and non-breastfed infants aged 6–23 months who received solid, semisolid, or soft foods (also including milk for non-breastfed infants). Minimum meal frequency was defined as at least two times for breastfed infants aged 6–8 months, at least three times for breastfed infants aged 9–23 months, and at least two feedings of milk products for non-breastfed infants during the previous 24 h.
- **Minimum Acceptable diet**: Proportion of infants aged 6–23 months who receive a minimum acceptable diet (both minimum dietary diversity and minimum meal frequency) during the previous 24 h.

Data processing and analysis

These secondary data were imported from SPSS into the Stata file version. The data were then cleaned, categorized, and tabulated using Stata 16.0/MP software for Windows. The wealth index data were gathered by utilizing household assets such as land, materials, and utilities (electricity and water sources). After checking the assumptions, the index was built using principal component analysis (PCA). The outcome was ranked into five categories: poorest, poorer, middle, richer, and richest.

Finally, both descriptive and analytical analyses of variables were employed. In addition, univariable and multivariable binary logistic analyses were used to evaluate the independent and multiple effects of each variable on the dependent variable. In the univariable binary logistic regression analysis, a *p*-value of ≤0.25 was employed to select candidate variables for multivariable analysis.

Furthermore, the co-linearity between variables was determined using variance inflation factors (VIF). A *p*-value of ≤0.05 was used to declare statistical significance during multivariable analysis. For each odd ratio (ORs; adjusted and crude), the 95% CI was computed. During the final analysis, the model's fitness was checked (*p*-value ≥0.05).

Results

Sociodemographic characteristics

The average age (±SD) of infants was 14.04 (±4.59) months. Moreover, nearly one-third of the children were found between the ages of 11 and 23 months. The mean age ± SD of the mother/caregiver was 29.40 ± 5.29 years. The majority of the mothers/caregivers (173 [39.14%]) were found between the ages of 25 and 29 years. All of them were Orthodox by religion. The mean ± SD of family size among participants was 4.54 ± 1.51. Here, nearly three-fourths (328 or 74.21%) of the households were not enrolled in the Productive SafetyNet Program during data collection (either because they graduated from the program or were not enrolled initially) (Table 1).

Index child-related characteristics

The average ± SD of the birth interval between the two-consecutive infants from the index was 3.33 ± 1.66 years. The majority of index infants have been breastfed (427 or 96.61%). In this study, three-fourths of the mothers/caregivers started complementary foods at the age of 6 months for their child. Still, the rate of institutional delivery is very low (68 [15.38%]). Approximately 6% (25) of the mother gives extra food/beverages after delivery instead of colostrum (Table 2).

TABLE 1 Socioeconomic characteristics of the mother/caregiver of infants aged 6–23 months in South Gondar Zone, Northwest Ethiopia, 2017 (*n* = 442).

Variable	Categories	Frequency	Percent
Current maternal age (completed years)	15–19	11	2.49
	20–24	52	11.76
	25–29	173	39.14
	30–34	136	30.77
	35–39	36	8.14
	40–44	27	6.11
	45–49	7	1.58
Age of the child	06–11 months	142	32.13
	12–23 months	300	67.87
Household head	Husband/brother*	420	95.02
	Wife/sister*	22	4.98
PSNP status	Current users	114	25.79
	Not user and graduate	328	74.21
Marital status	Married	357	80.77
	Single	37	8.37
	Divorced and separated	48	10.86
Respondent's educational status	Unable to read and write	335	75.79
	Able to read and write	107	24.21
Husband's educational status	Unable to read and write	237	53.62
	Able to read and write	184	41.63
	Primary education and above	21	4.75
Respondent's occupation	Housewife	219	49.55
	Daily laborer	24	5.43
	Farmer	199	45.02
Husband's occupation	Daily laborer	26	5.88
	Farmer	416	94.12
Family size	≤4	247	55.88
	≥4	195	44.12
Wealth index	Very poor	88	19.91
	Poor	104	23.53
	Middle	70	15.84
	Rich	129	29.19
	Very rich	51	11.54

*This brother or sister is for orphanage children; these children's caregivers will be married or not.

TABLE 2 Obstetrics-related characteristics of the mother for infants aged 6–23 months in South Gondar Zone, Northwest Ethiopia, 2017 ($n = 442$).

Variable	Categories	Frequency	%
The age difference between the last two children	<2 years	157	35.52
	≥2 years	285	64.48
Breastfeeding status	Yes	427	96.61
	No	15	3.39
Age at starting of complementary feeding	At birth	34	7.69
	01–06 months	79	17.87
	At 6 months or later	329	74.43
Giving additional/other foods or beverages after delivery	Yes	25	5.66
	No	417	94.34
Bottle feeding	Yes	47	10.63
	No	395	89.37
History of ANC visit for the index child	Yes	397	89.82
	No	45	10.18
Place of delivery for the index child	Health facilities	68	15.38
	At home	374	84.62
Any illness in the last 2 weeks	Yes	125	28.28
	No	317	71.72
Hand washing practice	Good	367	83.03
	Poor	75	16.97

Level of a minimum acceptable diet among children

The mean (±SD) minimum dietary diversity score (MDDS) was 5.38 ± 1.04. The overall MDDS and minimum meal frequency (MMF) magnitudes were 79.86 (95% CI: 75.82, 83.50) and 82.58% (95% CI: 78.71, 86.00), respectively. The consumption of vitamin-A-rich fruits and vegetables was found to be zero, which could be due to a lack of awareness about these types of food, difficulty accessing them, or the belief that other fruits and vegetables provide sufficient quantity of vitamin A. The magnitude of the minimum acceptable diet (MAD) score was 66.52% (95% CI: 61.90, 70.90) (Table 3).

The highest proportion of adequate diet diversity scores (261 [59.05%]) was from households that either graduated from PSNP or that were not enrolled in this program. Besides, the level of an adequate minimum acceptable diet score among the current PSNP users was low (79 [26.87%]) among all adequate MAD scores (Table 4).

TABLE 3 Level of a minimum acceptable diet intake percentage by 6–23-month-old infants in South Gondar Zone, Northwest Ethiopia, 2017 ($n = 442$).

Intake related variables		Frequency	Percentage
Cereals and roots (number of foods the infants consumed)		392	88.69
Legumes and nuts (number of foods the infants consumed)		111	25.11
Other fruits and vegetables (number of foods infants consumed)		79	17.87
Eggs (number of foods the infants consumed)		17	3.85
Milk and its products (number of foods the infants consumed)		115	26.02
Flesh food (number of foods infants consumed)		1	0.23
Minimum dietary diversity	Non-adequate	89	20.14
	Adequate	353	79.86
Minimum meal frequency	Non-adequate	77	17.42
	Adequate	365	82.58
Minimum acceptable diet	Non-adequate	148	33.48
	Adequate	294	66.52

TABLE 4 Children's practice of the minimum acceptable dietary intake parameter with Productive SafetyNet enrolment status in the South Gondar Zone, Northwest Ethiopia, 2017 ($n = 442$).

Intake category		Currently enrolled in PSNPs	
		Yes	No
Minimum dietary diversity	Non-adequate	22	67
	Adequate	92	261
Minimum meal frequency	Non-adequate	17	60
	Adequate	97	268
Minimum acceptable diet	Non-adequate	35	113
	Adequate	79	215

Factors associated with a minimum acceptable diet among children

During the independent assessment, all other factors were assumed to be constant; being a part of a PSNP household was not associated with a minimum acceptable diet during factor assessment. In addition to this, we assessed the combined effect of the other variables, which were assessed by doing univariable and multivariable binary logistic regression models. In the univariable binary logistic regression analysis, caregiver/maternal, marital status, the age of the child, family size, the educational status of the father, the occupational status of the father, breastfeeding, extra food before 6 months, wealth index, and the place of delivery were the significant variables.

Finally, in multivariable binary logistic regression, marital status, the educational status of the father, child age, and places of delivery were the associated factors for the uptake of a minimum acceptable diet among infants aged 6–23 months (Table 5).

Here, infants of single women were 3.98 times (AOR = 3.98, 95% CI: 1.39, 11.40) more likely to have/receive MAD as compared to infants of married women. Infants aged 11–23 months were 2.82 times (AOR = 2.82, 95% CI: 1.78, 4.47) more likely to have/receive MAD. In addition, while we compared children's fathers who could not read and write, children's fathers who could read and write were 44% less likely (AOR = 0.56, 95% CI: 0.35, 0.89) to receive an inadequate minimum acceptable diet. In addition, infants born in health institutions were 3.14 times (AOR = 3.14, 95% CI: 1.47, 6.73) more likely to have MAD. Furthermore, infants from the wealthiest families are 73% (AOR = 0.27, 95% CI: 0.12, 0.64) less likely to have an insufficient MAD intake than their peers.

Discussion

Despite enormous intervention by stakeholders, in Ethiopia, chronic food insecurity and undernutrition remain significant public health problems that affect the nutritional status of infants (Central Statistical Agency (Ethiopia) ICF International, 2014; Haile et al., 2016). In Ethiopia, PSNP was implemented to prevent existing household asset reduction and increase consumption by poorer/poorest household members. Being a part of this program may help to avoid the risk of food self-insufficiency or acute shortage and to build assets. Socioeconomic status is a necessary factor for optimal health (Fotso and Kuate-Defo, 2005; Gwatkin et al., 2007), which is determined using the wealth status or possession score from selected household items (Houweling et al., 2003; Mohsena et al., 2010), which influences the proportion of a minimum dietary diversity, meal frequency, and minimum acceptable diet directly or indirectly.

The magnitudes of the overall minimum dietary diversity score, minimum meal frequency, and overall minimum acceptable diet were 79.86, 82.58, and 66.52%, respectively. In this study, the proportion of MAD is higher than that shown in the research conducted in Ethiopia, which ranges from 4.2 to 13.3% (Abeshu et al., 2016; Gizaw and Tesfaye, 2019; Mulat et al., 2019; Tassew et al., 2019). Similarly, the magnitude of MDDS and MMF is also high when we compared it with the study findings in North Showa, Ethiopia, which are 45 and 33%, respectively (Gizaw and Tesfaye, 2019). The possible reasons may be due to the difference in the data collection period and residential differences, household socioeconomic status, cultural differences, child feeding knowledge of the mother, existing interventions by stakeholders, and dietary habits.

Here, infants of single women were 3.98 times more likely to have/receive MAD when we compared them to infants of married women. This could be because single women might have a high decision-making capacity (Mulat et al., 2019), a small family size, and increased care.

Infants aged 11–23 months were 2.82 times more likely to have/receive MAD, which is consistent with EDHS data analysis findings (Tassew et al., 2019). The study findings are similar in Ghana and Uganda (Ng et al., 2012; Na et al., 2018). However, according to the study findings in Wolita Sodo, Ethiopia (Mekonnen et al., 2017), infants age and infants receiving MAD are inversely related. The possible cause might be the change in mothers'/caregivers' knowledge, behavior, and meal frequency due to the diminishing breast milk production. In addition, as infants grow and develop, their bodies may demand more nutrients, leading to an increase in food cravings.

When compared to infants whose fathers could not read or write, those whose fathers could read and write were 44% less likely to receive a minimum acceptable diet. The result of this study is invariant with the research done in Oromia, Ethiopia (Mulat et al., 2019), Enemay District, Northwest Ethiopia (Gessese et al., 2014) and is consistent with EDHS data analysis findings (Tassew et al., 2019). Additionally, it is a strong predictor similarly in South Asia, Bangladesh, and Nepal (Kabir et al., 2012; Senarath and Dibley, 2012; Khanal et al., 2013). The possible reason might be the link between educational status, income, exposure to mass media, and knowledge about healthy dietary habits.

Furthermore, infants born in hospitals were 3.14 times more likely to have MAD than those born at home. The study finding is similar to the study conducted in Oromia, Ethiopia (Mulat et al., 2019). This might be due to appropriate counseling by healthcare providers on proper IYCF practices, their importance, and their effect on optimal health.

Furthermore, infants from the wealthiest families are 73% less likely to have insufficient MAD than their peers. This finding

TABLE 5 Factors associated with MAD uptake among infants aged 6–23 months in South Gondar Zone, Northwest Ethiopia, 2017 ($n = 442$).

Variable			MA	COR (95% CI)	AOR (95% CI)
	Adequate	Inadequate			
Marital status	Married	228	129	1	1
	Single	32	5	3.62 (1.38, 9.52)	3.98 (1.39, 11.40)*
	Divorced and separated	34	14	1.37 (0.71, 2.65)	1.22 (0.56, 2.64)
Child Age	6–11 months	73	69	1	1
	12–23 months	221	79	2.64 (1.74, 4.01)	2.82 (1.78, 4.47)*
Family size (mean)	≤4	74	173	1	1
	>4	74	121	0.69 (0.47, 1.04)	0.96 (0.60, 1.52)
Father educational status	Unable to read or write	170	67	1	1
	Able to read and write	110	74	0.58 (0.39, 0.88)	0.56 (0.35, 0.89) *
	Above primary school	14	7	0.79 (0.30, 2.03)	0.59 (0.20, 1.71)
Father occupational status	Daily laborer	20	6	1	1
	Farmer	274	142	0.58 (0.22, 1.47)	0.67 (0.23, 1.91)
Breastfeeding	Yes	281	146	1	1
	No	13	2	3.38 (0.75, 15.16)	3.30 (0.66, 16.41)
Extra food before six months	Yes	21	4	1	1
	No	273	144	0.36 (0.12, 1.07)	0.97 (0.27, 3.47)
Place of delivery	Health facilities	58	10	3.39 (1.68, 6.85)	3.14 (1.47, 6.73) *
	At home	236	138	1	1
Wealth index	Very poor	70	18	1	1
	Poor	78	26	0.77 (0.38, 1.52)	0.96 (0.45, 2.06)
	Middle	46	24	0.49 (0.24, 1.01)	0.50 (0.23, 1.09)
	Rich	80	49	0.41 (0.22, 0.78)	0.57 (0.28, 1.18)
	Very rich	20	31	0.16 (0.07, 0.35)	0.27 (0.12, 0.64)*

*Significant during multivariable analysis ($p < 0.05$), 1 = Reference, AOR, adjusted odd ratio; COR, crude odd ratio; MDA, minimum acceptable diet.

is consistent with other studies that showed that infants in high-income households consume a more diverse diet than those in low-income households (Gessese et al., 2014; Solomon et al., 2017). This could be due to household purchasing power for a variety of foods. Similarly, a high income may be associated with a higher level of education, which may increase knowledge about proper child feeding.

Limitations of the study

One of the limitations of this study is that it could not link MAD to specific causes; it was difficult to establish a possible causality, and it was unable to include knowledge, attitude, and practice of caregivers/mothers related to infant and young child feeding (IYCF) due to the nature of the data (secondary data), and recall-related problems. Finally, the IYCF program indicators were not a part of this study.

Conclusions

Nearly two-thirds of the infants had/received a minimum acceptable diet. Moreover, households' Productive SafetyNet status has no statistical impact, and the proportion of the minimum acceptable diet was low in the study area. There were program phases or stages implemented in the past before phase 4 (productive SafetyNet program) was launched. So, this is the comparison of phase 4 (the current) with the past (phase 3 and before it). Here, marital status, the educational status of the father, the child's age, and the place of delivery were the associated factors for the uptake of a minimum acceptable diet among infants aged 6–23 months.

Based on this, stakeholders should have to strengthen the PSNPs through the integration of current nutrition and other health-related strategies/programs to increase MAD uptake. Moreover, health professionals shall have to provide health and nutrition education and counseling based on the child's age, the father's educational status, the marital status of the woman or caregiver, and the place of delivery through other child and reproductive healthcare services.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving human participants were reviewed and approved by Ethical Review Committee of Debre Tabor University. The patients/participants provided their written informed consent to participate in this study.

Author contributions

ME and AG made the draft of the proposal for data collection. ME, AG, BK, DT, ST, and YS contributed to the acquisition and analysis of data and to the interpretation or discussion, the results of the manuscript, the analysis, interpretation, discussion and results, and revised the manuscript. All the authors read and approved the final manuscript.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Sustainable intensification of agriculture as a tool to promote food security: A bibliometric analysis

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Sustainable intensification (SI) of agriculture is required to satisfy the growing populations' nutritional needs, and therefore food security while limiting negative environmental impacts. The study aims to investigate the global scientific output of sustainable intensification research from 2010 to 20 August 2021. The data was retrieved from the Web of Science (WoS) Core Collection and was analyzed using a bibliometric method and VOS viewer to determine the most productive countries and organizations by collaboration analysis, including the keywords to analyze the research hotspots and trends, and the most cited publications in the field. From the 1,610 studies published in the theme of sustainable agriculture by 6,346 authors belonging to 1,981 organizations and 115 countries, the study found an increased number of publications and citations in 2020, with 293 publications and 10,275 citations. The United States ranked highest in countries collaborating with the most publications in the field. The occurrence of keywords like "food security", "climate change", "agriculture", "ecosystem services", "conservation agriculture", "Sub-Sahara Africa", "Africa", "biodiversity", and "maize" in both author and all keywords (author and index) reveal the significance of sustainable intensification in Africa, as a solution to food insecurity under climate change conditions. The availability of funding agencies from big economies explains the growing interest by developing countries in the SI of agriculture research due to the growing population, food insecurity, and access to limited land for farming.

KEYWORDS

sustainable intensification, food security, climate change, climate-smart agriculture, agriculture

1. Introduction

Soil has become one of the world's most vulnerable resources due to climate change, land degradation, and biodiversity loss. The expansion of arable land is associated with ecological and social costs, and hence, avoiding the conversion of natural land to arable land is beneficial for biodiversity (Phalan et al., 2011) and other important ecosystem services (Garnett et al., 2013). For enhanced management of natural resources with attention to minimizing trade-offs between profitability and productivity, sustainable intensification (SI) approaches have been promoted (Garnett et al., 2013; Kaczan et al., 2013; Pretty and Bharucha, 2014). Based on Godfray et al. (2010), Pretty et al. (2011), and Giller et al. (2015), important features of SI include the production of more output per unit area, increasing the flow of environmental services, and the accumulation of natural, social, and human capital. Based on Pretty (1997), and Garnett and Godfray (2012) SI was initially used in the mid-1990s in smallholder African agriculture. It was also highlighted by Kassie et al. (2015) and David et al. (2016), that global research on SI practices is mainly concentrated in Africa where farmers are the main research object, including their behavior choices in the practice of SI. In Africa, SI is important since it provides possibilities for increased crop production per unit area while addressing features of sustainability such as social, economic, political, and environmental impacts (FAO, 2006). Sustainable intensification (SI) is more extensively used (Tittonell, 2014; Petersen and Snapp, 2015) than ecological and agroecological intensification, and to meet the current food security demand, SI has received much prominence as a key approach (Smith et al., 2017). Evidence has increasingly shown that sustainable agricultural practices have the potential to meet sustainability and boost agricultural productivity (Rockström et al., 2017). However, based on the same author, production increases don't necessarily mean that yields should increase at any cost or everywhere as yield increase in some areas is compatible with environmental improvements, while in others, land reallocation and reductions in yield is required to ensure sustainability and to deliver environmental benefits like carbon storage, recreation, biodiversity conservation, and flood protection. The global challenges of food security require global responses, and the fundamental problems of food security are addressed with several mechanisms such as SI of agriculture and the United Nations Sustainable Development Goal goal to end hunger. The goal to fight climate change and end food insecurity is clearly specified under goal 2 of the SDGs, which is to "end hunger, improve nutrition, achieve food security and promote sustainable agriculture." Nevertheless, without arable land, soil remediation, or reclamation, it would be difficult to achieve this goal. Hence, mapping of research trends and existing knowledge trajectories are important in order to hypothesize and reach a conclusive solution toward SI of agriculture. Due to the lack of food security in the various parts of the globe, SI can play a significant role in bridging the food insecurity confronting the agricultural sector, only if the knowledge of current research trajectories is understood. One of the means to underscore what has been done, and what gaps remain and to understand present research focus, is conducting bibliometric mapping. It is important to dissect and conduct knowledge mapping through bibliometric analysis. One of the significances of this study is to highlight the knowledge gaps and how SI could be utilized as remediation process. For example, in 2015, Okem observed that despite the achievements of the Comprehensive African Agricultural Development Programme (CAADP), food security in Africa continues to be a persistent problem (Okem, 2015). Even recently, the food insecurity problem still persists (Ajibade, 2020; Ngcamu and Chari, 2020; Ojo et al., 2022). Furthermore, a recent study conducted in Canada highlighted that food insecurity is still a prevailing challenge in Canadian household (Hutchinson and Tarasuk, 2022). It is therefore, imperative to understand whether debates about food insecurity, and SI understood the inseparability of these two concepts.

To highlight the global research trends in the field of sustainable intensification (SI) of agriculture, a bibliometric analysis was used based on publications retrieved from the Web of Science (WoS) Core Collection database between 2010 and 2021 while Vosviewer software was used to visualize pertinent results. Bibliometric analysis has been used in various fields, and as an important quantitative analysis tool, as it can effectively describe the overall trend of subject or field development (Hirsch, 2005; De Bakker et al., 2016). Based on the main research findings, key research areas concerning sustainable agricultural intensification that need improvement in the future are explored.

1.1. Literature search

Due to the rapidly growing global population, sustainable intensification (SI) of agriculture has gained more attention, especially in Sub-Saharan Africa where the population is rapidly increasing (Bello-Schünemann et al., 2017), together with a high increase in soil degradation (Tully et al., 2015), that is aggravated by climate change (IPCC, 2007). Also, with ∼40% of the world's terrestrial surface being transformed to agriculture (Ramankutty et al., 2008), in 2018, only 9% of the world's agricultural land had undergone SI (Pretty et al., 2018).

Agricultural technologies usually promoted as supporting pathways to sustainable intensification (SI) include Climate Smart Agriculture (CSA) and Conservation Agriculture (CA), and Integrated Soil Fertility Management (ISFM) (Place et al., 2003; Giller et al., 2015), including agroforestry, carbon benefits, integrated pest management, and ecosystem services (Mbow et al., 2019). Based on Mbow et al. (2019) and Xie et al. (2019), numerous SI practices can be grouped into 10 approaches and categories depending on their application as explained in the review study of Nciizah et al. (2022). The approaches mentioned in their study, include irrigation water management, soil management, increased agricultural system diversity, and integrated pest management among others. These approaches have the potential to improve food security. For instance, in Savannah regions, the Comprehensive Assessment of Water Management in Agriculture (2007), showed a large potential in upgrading rainfed agriculture by improving rainwater harvesting. For example, in semi-arid areas of Burkini Faso where smallholder farmers are using planting pits to rehabilitate degraded land and harvest rainwater for sorghum and millet cultivation, 300,000 hectares of land have been rehabilitated, with an annual increase of 80,000 tons of food produced (Reij et al., 2009). Rusinamhodzi et al. (2011) reported significant yield gains for smallholder farmers who adopted conservation agriculture in several parts of Sub-Saharan Africa. For example, in Mozambique yield increases of up to 27% were reported by Thierfelder and Wall (2012), and these production increases were associated with increased soil organic carbon, which improved biological and physical soil processes. It is worth noting that, the benefits of adopting SI practices have been reported in other countries as well. For example, in Brazil, it was reported by Altieri et al. (2012) that producers who adopted conservation agriculture under severe drought conditions from 2008 to 2009, experienced smaller maize yield losses of around 20% on average, compared to 50% experienced by conventional maize producers.

However, through the lens of climate change, climate-smart agriculture (CSA) aims at achieving the same objectives of food security as sustainable agriculture. In Africa, CSA can increase productivity and resilience while reducing the vulnerability of millions of smallholder farmers (Sullivan et al., 2012). Climate-smart agriculture (CSA) is based on CA, agroecology, and organic farming [Department of Agriculture, Forestry and Fisheries (DAFF), 2014], in countries like South Africa. CSA and agroecological agriculture share their objectives of food security and climate change. Agroecology is presented by the Global Alliance for Climate-Smart Agriculture (GACSA) (2014), as a component of CSA and SI, but CSA and agroecology are different in other aspects. CSA desegregates three dimensions of sustainable development (i.e. economic, social, and environmental) by addressing climate change and food security. There are, however, some disputes about the kind of practices and technologies which should be considered in CSA. It was interesting to find that researchers like Campbell et al. (2014) consider CSA as complementary to SI of the agricultural production system. Their views agree with Garnett and Godfray (2012), who noted that using sustainable agricultural intensification increased crop yields without harmful environmental impacts and cultivation of more agricultural land. CSA is comprised of three pillars: sustainable development, SI and green economy, and its connection with conservation agriculture-based SI, organic farming, CSA, and food security (Figure 1).

Recent study indicated that in many countries where food insecurity is a challenge, governments have developed or are in progress of developing integrated food and/or nutrition security strategies (IFSSs; Figure 2) (Ajibade, 2020). These strategies are explicit governmental attempts to fundamentally redesign or align goals, instruments, and capacities to achieve the four basic dimensions of food security (Rayner and Howlett, 2009) such as food availability, access, utilization, and stability. For instance in South Africa, the approval of the National Policy for Food and Nutrition Security Strategy in 2013 indicated the recognition by the government of the need for a coordinated approach to addressing food security (Nkwana, 2015). The policy acknowledges the complex nature of food security and aims to provide a framework for synergy between the various programs and policies in place.

2. Materials and methods

2.1. Data collection

The data were retrieved on the 20th of August 2021. The relevant literature used in the present study was collected from the Science Citation Index Expanded (SCI-E), Social Science Citation Index (SSCI), Conference Proceedings Citation Index-Science (CPCI-S), Book Citation Index-Science (BKCI-S), and Emerging Sources Citation Index (ESCI) in the Web of Science (WoS) Core Collection. In bibliometric studies, the SCI-E is the frequently used database in the WoS Core Collection (Yu and Liao, 2016; Shi et al., 2019) and is also the most reputational academic journal system where published papers are ensured with a rigorous peer-review process (Wang and Wang, 2019; Li et al., 2020). WoS covers a wide range of research papers from different fields, and this includes over 50,000,000 classified research papers, 15,000 journals in 150 research areas and 251 categories (Merigó and Yang, 2017). WoS has the highest quality (Mora et al., 2017) and covers many research papers from different fields. The search terms were "sustainable intensification" OR "Sustainable Agricultural Intensification" OR "Sustainable Intensification of Agriculture" OR "Agricultural Sustainable Intensification," and these terms appeared in the title, abstract, author keywords, and keywords plus to ensure relevant literature. The time range was set from 2010 to 20 August 2021, and 1,610 research papers were obtained.

2.2. Methodology and analysis tools

The review of the literature in the study was done through a bibliometric analysis. Bibliometric analysis is widely used in hotspot research (Yeung et al., 2017) and the development of the whole subject field (Merigó and Yang, 2017). Based on Zou et al. (2018), the method uses quantitative analysis and statistics to investigate the development of the research field and knowledge structure. Also, by bibliometric analysis it is possible to construct a network based on the co-authorship or relationship between countries, organizations, journals, and authors (Sweileh et al., 2016), including keywords about the field (Chen et al., 2016). The keyword co-occurrence network [author and all keywords (author and index)], co-authorship, overlay and density visualization were obtained using the VOSviewer technique based on Van Eck and Waltman (2010) VOS algorithm. Based on Nobanee et al. (2021), the technique efficiently combines literature and from the retrieved publications establishes similarities and important themes among the publications.

It is worth noting that the basic color view of a topic in VOSviewer depends on the ordinary density rule. Therefore, in the visualization map, color of a point is determined by the item density of the point. The average distance between two items is denoted by $\bar{\mathbf{d}}$ as shown in equation 1:

$$\bar{\mathbf{d}}=\frac{\mathbf{2}}{\mathbf{n\,(n-1)}}\sum\nolimits_{\mathbf{i\leq j}}\left\|\mathbf{x_i}-\mathbf{x_j}\right\| \tag{1}$$

Then, the item density D (x) of a point x= ($x1$, $x2$) is defined by equation 2.

$$\mathbf{D\,(x)}=\sum\nolimits_{\mathbf{i=1}}^{\mathbf{n}}\mathbf{w_i k}\left(\frac{\left\|\mathbf{x}-\ \mathbf{\overset{i}{x}}\right\|}{\mathbf{h\bar{d}}}\right) \tag{2}$$

where k: $[0, \infty) \rightarrow [0, \infty)$ denotes a kernel function; w_i weight of item i, which is the total number of occurrences of item i, while $h > 0$ denotes the kernel width, with the kernel function k as a non-increasing parameter. VOSviewer uses the Gaussian function shown in Equation 3 below.

$$\mathbf{K\,(t)}=\exp\left(-\mathbf{t^2}\right) \tag{3}$$

The function in Equation 3 follows from Equation 2 that the item density ($D(x)$) of a point in the visualization map depends on the number of neighboring items and weights of the items. Therefore, the higher the number of neighboring items and the smaller the distances between these items and the point of interest, the higher the $D(x)$ will be. In addition, the higher the weights of the neighboring items are, the higher the item density will be (Xia and Zhong, 2021).

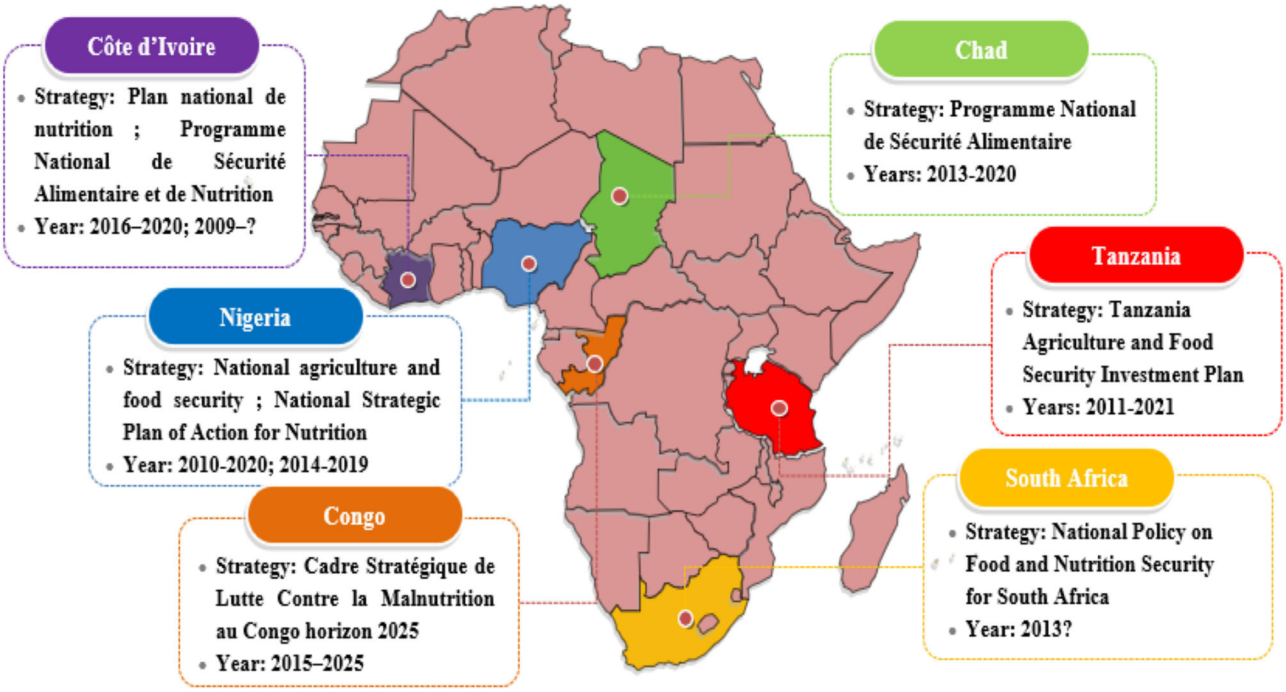

FIGURE 1
Integrated food and/or nutrition security strategies in selected countries of Sub-Saharan Africa.

3. Results

3.1. Document types

The number of publications was associated with Sustainable intensification (SI) in various document types like articles, reviews, editorial material, early access, etc. (Figure 3). The results indicate that the most frequently used category of research papers is articles, as they account for 80.44% (1295) of the total publications. The second most used communication channel category in SI is review articles, comprising 13.29% (214) of the publications. For other documents like book chapters, proceedings papers, editorial materials, early access, correction, etc., each had less than 100 publications. The least used communication approach is books, letters, and news items, contributing 0.06% of publications.

3.2. Publication output and citation

The number of publications and the frequency of citations are used to determine the academic influence of the authors (Liang et al., 2018). Based on Sevinc (2004), citation analysis is one of the parameters used to assess the quality of research papers published in scientific, social sciences, and technology journals. The annual trend of research papers associated with SI from 2010 to 20 August 2021 is shown in Figure 4. From 2010 to 2021, 1,610 documents on the SI field were retrieved from the Web of Science Core Collection database. The first research papers related to SI were published in 1997 by Pretty, Bebbington, and Reardon et al. (Bebbington, 1997; Pretty, 1997; Reardon et al., 1997). The number of publications showed an exponential growth with less than 10 publications recorded in 2010. From 2010 to 2020, the number of publications increased by 97.61%, with the highest number of publications in 2020 (293 publications). The same trend regarding the number of citations per year was observed, as shown by an exponential growth trend in the annual citations and an increased number of citations from 2 in 2010 to 7903 by 20 August 2021, with the highest increase of 10,275 citations in 2020.

3.3. Annual publications per country

The annual publications from the top 10 most productive countries in the SI field are shown in Figure 5. The United States was the most productive country, with steady growth in research and a contribution of 22.42% during the study period (from 2010 to 20 August 2021). England ranked second with an annual increase in publications since 2014 and had the highest number of publications in 2011 and 2013, higher than the USA. Kenya was in the 5th position with a contribution of 139 publications (8.63%) and was the only African country in the top 10 countries between 2010 and 2021. It is worth noting that European countries like the Netherlands, Germany, and France together had the highest total contribution of 28.01% (451 publications).

3.4. Subject categories, research area, funding agencies, and organization analysis

The top 10 subject categories, research areas, funding agencies, and organizations in the SI field between 2010 and 20 August 2021 are shown in Table 1 below. All the 1,610 publications on studies related

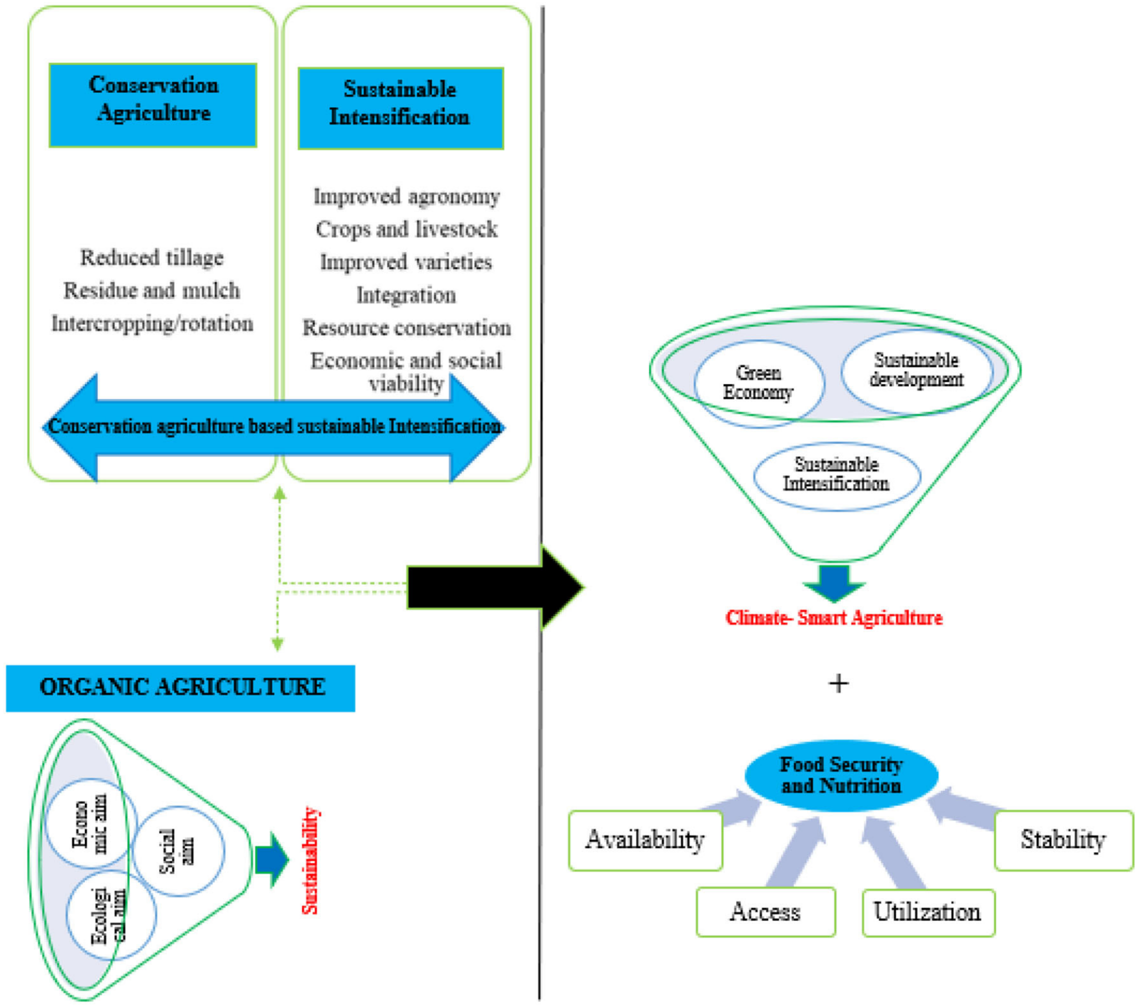

FIGURE 2
The connection between sustainable intensification, innovative agricultural practices, and food security and nutrition.

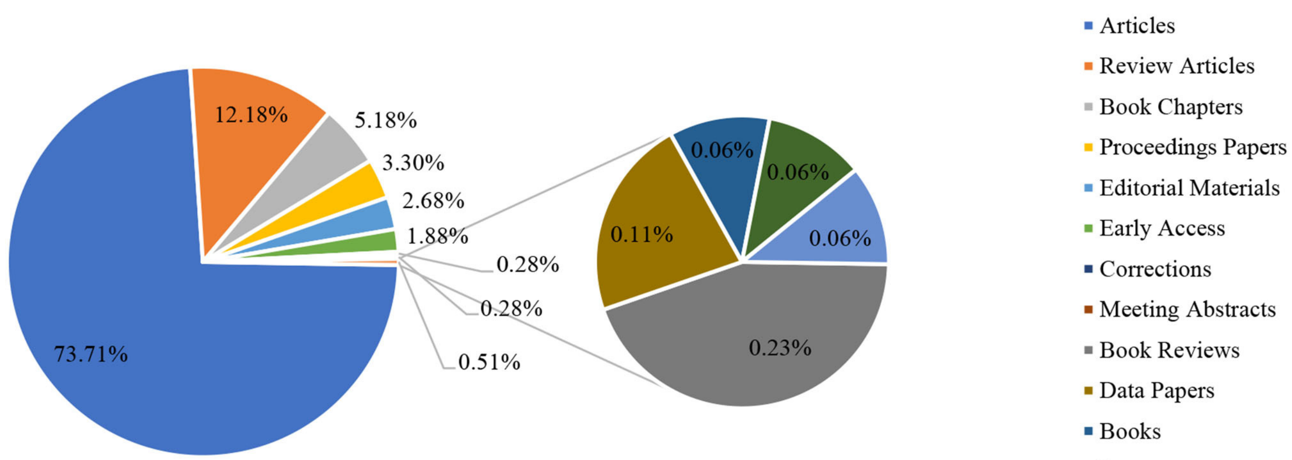

FIGURE 3
Document types of sustainable intensification research articles from 2010 to 20 August 2021.

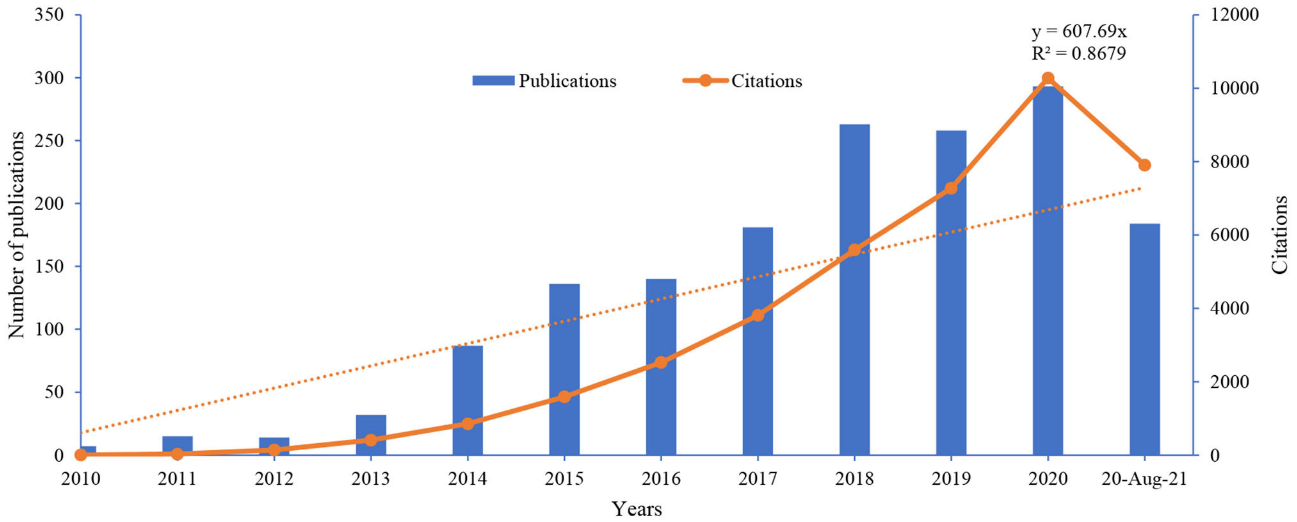

FIGURE 4
Publication output and citations from 2010 to 20 August 2021.

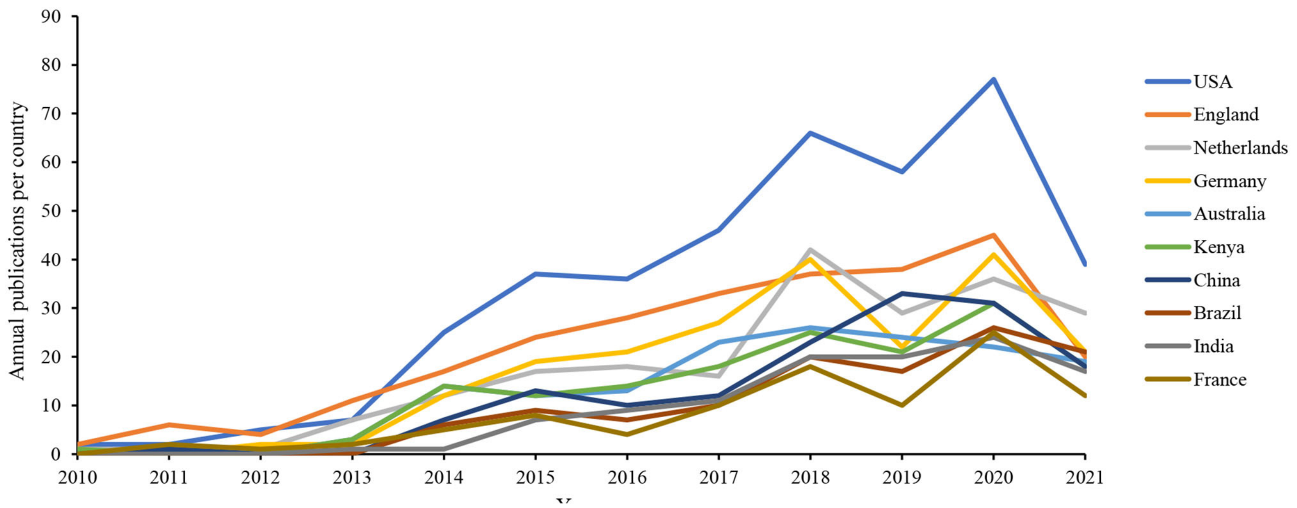

FIGURE 5
Trends in the number of publications per country from 2010 to 20 August 2021.

to the SI field are grouped according to 88 subject categories. Most of the publications analyzed in the present study are in "Environmental Science," with 429 research papers, which account for 26.65% of the total publications. The second-ranking subject category is "*Agronomy*" with a contribution of 18.32% (295 publications), followed by "*Agriculture Multidisciplinary*" (281, 17.45%), "*Green Sustainable Technology*" (262, 16.27%), "*Environmental Studies*" (220, 13.67%), "*Ecology*" (143, 8.88%), etc. Other fields like "*Agricultural economics policy*," and "*Soil*" each have <100 documents. Research on SI is mostly published in the field of "*Agriculture*" (771 publications), followed by "*Environmental Science Ecology*" (555 publications), "*Science Technology*" (319 publications), "Food Science Technology" (120 publications), "Plant Science" (100 publications). The top funding agency and organization is the Consultative Group for International Agricultural Research (CGIAR), a global partnership involved in research dedicated to alleviating rural poverty, ensuring more sustainable management of natural resources, increasing food security, and improving human health and nutrition.

4. Global sustainable intensification of agriculture research

The importance of sustainable intensification (SI) research can be reflected by the distribution of publications in different countries, as shown in Figure 6. For instance, 115 countries were involved in SI research between 2010 and 20 August 2021. Of the top 10 most influential countries, there are four European countries (England, the Netherlands, Germany, and France), two American countries (the USA and Brazil), two Asian countries (China and India), and only one African country (Kenya). Moreover, Africa ranked second based on North and South America's overall contribution. In North

TABLE 1 Top 10 subject categories, research areas, funding agencies, and organizations in SI research from 2010 to 20 August 2021.

RO	Subject categories	RC	Research area	RC
1	Environmental sciences	429	Agriculture	771
2	Agronomy	295	Environmental sciences ecology	555
3	Agriculture multidisciplinary	281	Science technology	319
4	Green sustainable science technology	262	Food science technology	120
5	Environmental studies	220	Plant sciences	100
6	Ecology	143	Business economics	73
7	Food science technology	120	Biodiversity conservation	60
8	Plant sciences	100	Engineering	47
9	Agricultural economics policy	80	Geography	38
10	Soil Science	76	Meteorology atmospheric sciences	38
RO	Funding agencies	RC	Organizations	RC
1	Consultative Group for International Agricultural Research/CGIAR	127	Consultative Group for International Agricultural Research/CGIAR	282
2	European Commission	114	Wageningen University Research	168
3	UK Research Innovation/UKRI	97	International Maize Wheat Improvement Center CIMMYT	86
4	United States Agency for International Development/USAID	95	Alliance	66
5	National Natural Science Foundation of China/NSFC	67	Commonwealth Scientific Industrial Research Organization CSIRO	64
6	Biotechnology And Biological Sciences Research Council/BBSRC	50	International Livestock Research Institute/ILRIIlri	57
7	Natural Environment Research Council/NERC	43	Michigan State University	54
8	Bill & Melinda Gates Foundation	40	National Research Institute for Agriculture, Food and the Environment/INRAE	48
9	Federal Ministry of Education Research/BMBF	37	International Center for Tropical Agriculture/CIAT	46
10	European Commission Joint Research Center/EU JRC	33	University of California (UC) System	46

RO, ranking order; RC, record count.

and South America, there were four countries with more than 50 publications, while in Africa, there were three countries that had more than 50 publications.

5. Collaboration analysis

5.1. Authors and collaborations

Out of 6,346 authors involved in the SI field, there are 119 authors with at least five co-authored publications grouped in 23 clusters differentiated by colors, with 288 links (i.e., the relationship between authors) and a total link strength (TLS) of 781 which denotes the cumulative strength of the links of a publication with other publications, as displayed by the network visualization map and density visualization in Figure 7. The co-authorship network shows the existence of co-authorship and the relation between authors of scientific research papers (Van Eck and Waltman, 2011). The nodes' size represents the author's research output, and the circles in the same color show the cluster the authors are associated with. The results showed that the maximum number of co-authored publications by each of the authors was 29. The top 5 and top 10 authors in Table 2 have contributed to 5.60 and 9.63% of the total publications. The first-ranked author Giller, K. E., from the Netherlands, co-authored 29 (1.80%) publications, followed by Jat, M. L., from India, and Pretty, J. from England, with a contribution of 17 (1.06%) and 15 (0.93%) publications. The most cited author was Pretty, J. with 1614 citations, followed by Giller, K.E. with 749 citations.

5.2. Countries and collaborations

The analysis of research output between countries is useful in identifying the most productive countries in SI research. The difference between the number of documents and citations by country is shown in Table 2. A total of 115 countries contributed to the research output of the SI field. Of the 115 countries, only 72 met a minimum number of five documents and were grouped in seven clusters that are differentiated by colorscolors with 1,065 links (i.e., the relationship between countries) and a total link strength (TLS) of 4,013, as displayed by the overlay visualization in Figure 8. The link strength was used as a quantitative index to show relations between two nodes (Pinto et al., 2014). The overlay visualization was used to show the earliest and most recent contributing countries in the SI field in terms of the average publication years. For instance, based on the overlay visualization, countries like Uruguay, Argentina, South Korea, Egypt, Chile, Hungary etc., have the most recent publications in the SI field. While countries like England, Malawi, Nigeria, Austria, Wales, Portugal etc., have the earliest publications. The USA was the most productive contributor to the SI research with 398 publications, and a TLS of 609. The second most productive

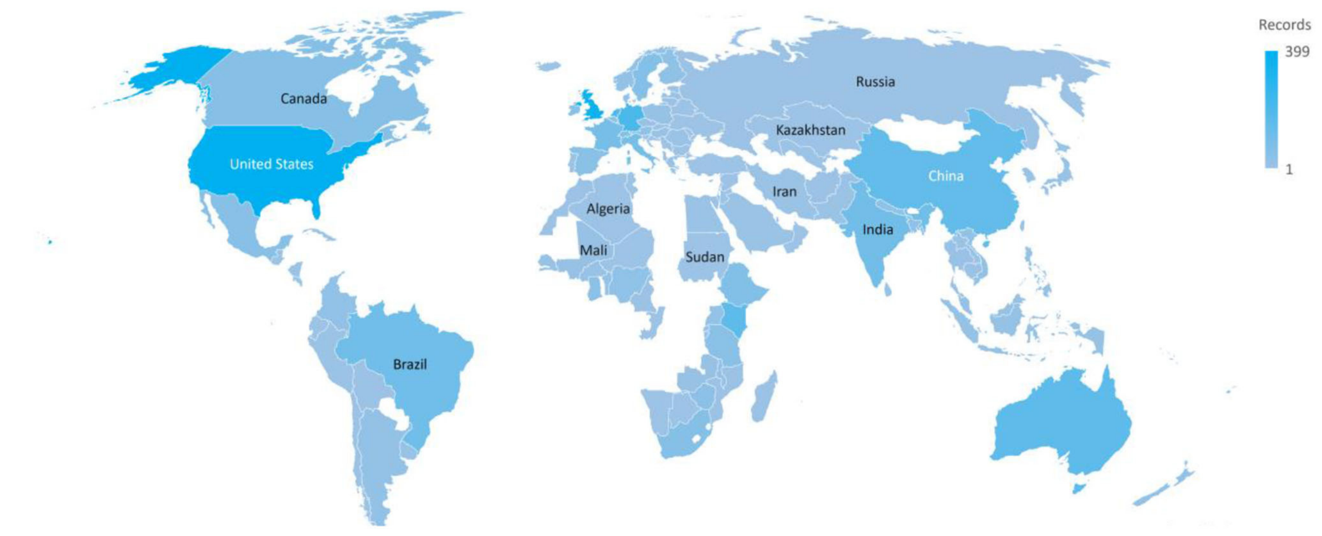

FIGURE 6
Global literature on the topic of sustainable intensification from 2010 to 20 August 2021.

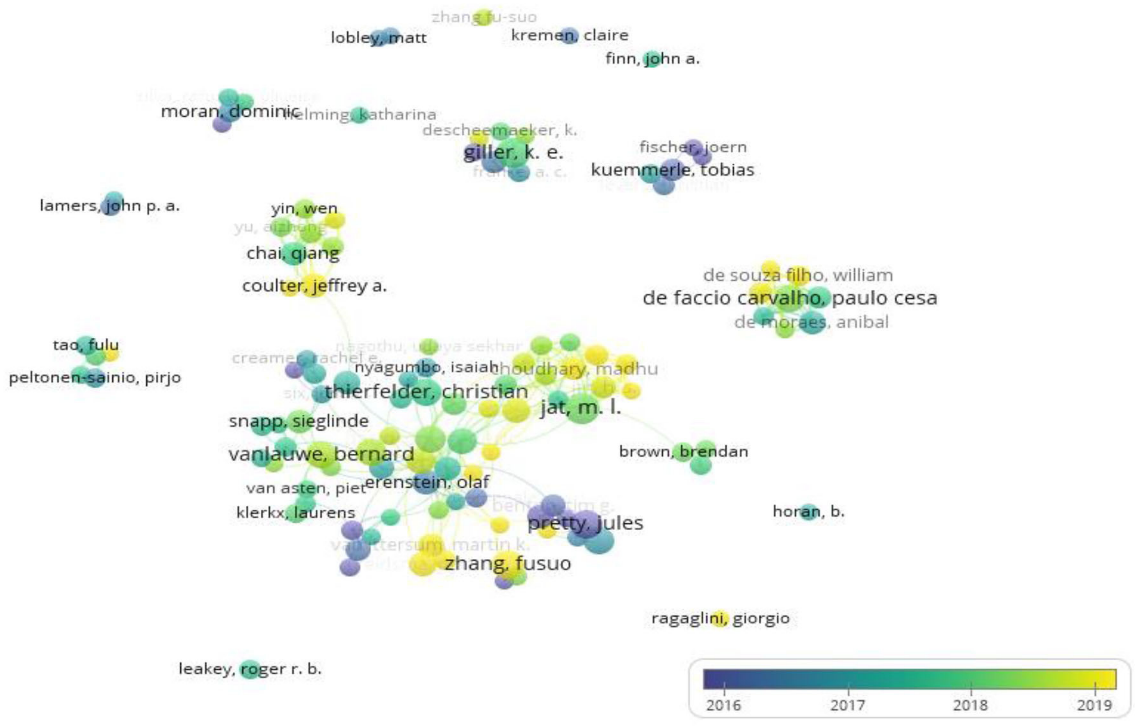

FIGURE 7
The overlay collaboration network of author from 2010 to 20 August 2021.

country was England, with 262 publications and was the earliest contributor to the SI research, as seen in Figure 8. The same trend was observed with the number of citations, with the USA being the top country, with 16,773 citations followed by England with 8,997 citations. Of the 10 productive countries, 60% are developing countries, and 40% are developing countries like Kenya, China, Brazil, and India. Compared to the rest of the top 10 most productive countries, China, Brazil, and India had interacted with <50 countries. Nodes represent the countries, and the size proportion is a function of publications. The lines that join the nodes show the existing interconnection between countries, i.e., it shows the collaboration's strength. The distance between two nodes or countries in the network visualization signifies topic relative strength and similarities, with stronger relations with the shorter distance. The Netherlands, France, and Kenya had close co-operations, showing some similarities in SI research.

TABLE 2 Top 10 most productive authors co-authorship in SI research from 2010 to 20 August, 2021.

RO	Author	TLS	RC	Citations	Country	TLS	RC	Citations
1	Giller, K. E. (Netherlands)	33	29	749	USA	609	398	16,773
2	Jat, M. L. (India)	43	17	281	England	444	262	8,997
3	Pretty, J. (England)	12	15	1,614	Netherlands	520	207	5,650
4	Zhang, F. (China)	6	15	546	Germany	371	204	5,039
5	Vanlauwe, B. (France)	13	14	303	Kenya	419	157	4,523
6	Lal, R. (USA)	2	14	323	Australia	396	156	5,911
7	Carvalho, PCF (Brazil)	46	13	239	China	202	146	3,464
8	Baudron, F. (Zimbabwe)	20	13	253	Brazil	184	116	2,684
9	Thierfelder, C. (Zimbabwe)	15	13	366	India	208	109	1,813
10	Groot, Joroen C.J. (Netherlands)	20	12	58	France	278	95	2,570

RO, ranking order; TLS, total link strength; RC, record count.

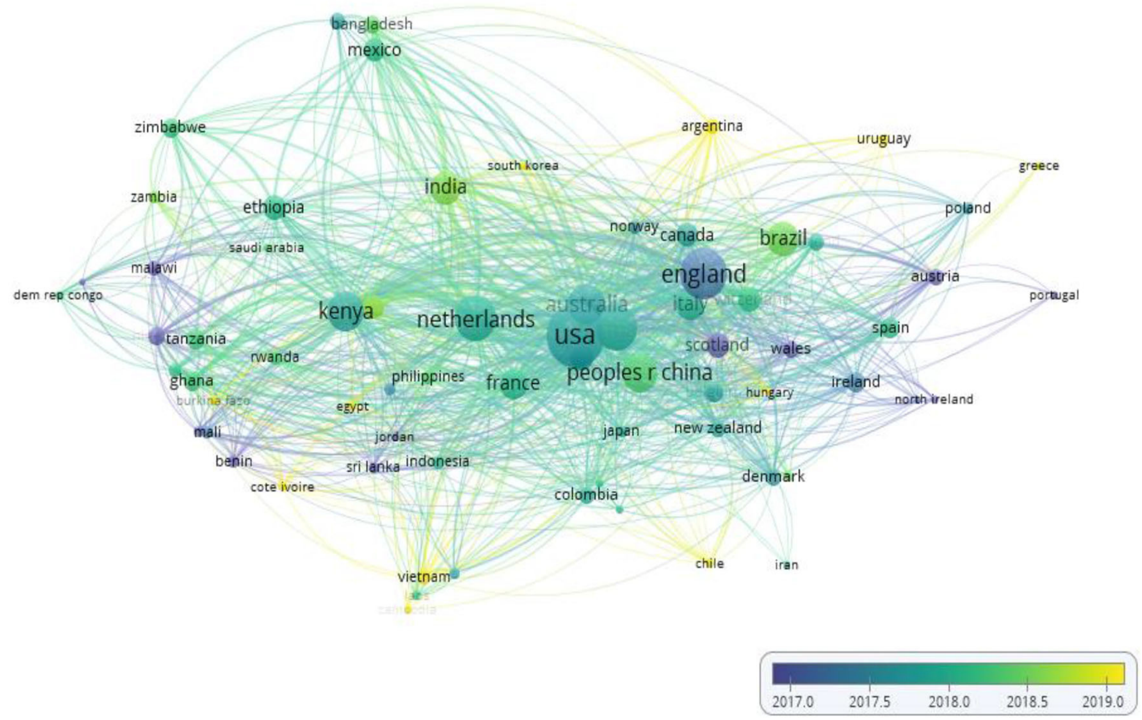

FIGURE 8
The overlay visualization of the country/region collaboration from 2010 to 20 August 2021.

6. Co-occurrence analysis

The co-occurrence analysis of keywords has proven to be an effective tool for monitoring and developing science and programs (Gao et al., 2017). Also, the analysis was used in the present study to evaluate the hot topics, including the research trends (Chen et al., 2016) and future potential topics (Ding and Yang, 2020) in the SI field and to reveal some neglected areas in the field (Koo, 2017). The density visualization was selected to understand the general structure and show the most imperative areas on the map (Chawla and Davis, 2013) (Figures 8, 9A). The top 20 co-occurrence keywords shown in Table 3 occurred in the abstract and title fields. In all the 3,876 authors' keywords and 6,526 all keywords retrieved from the database, only 216 and 611 keywords met a threshold of a minimum of five co-occurrence keywords. Figure 9A visualizes 10 different clusters, 2,303 links, and a total strength of 3,711 author keywords, while Figure 9B visualizes nine different clusters, 23,795 links, and 46,966 of all keywords. The size of the nodes shows the occurrence of the author and all keywords, and the larger the node in the network visualization is, the more a keyword has been co-selected in the SI field. The line joining the two nodes shows that the keywords appeared together, and the thicker the line, the co-occurrence they have (Gu et al., 2017).

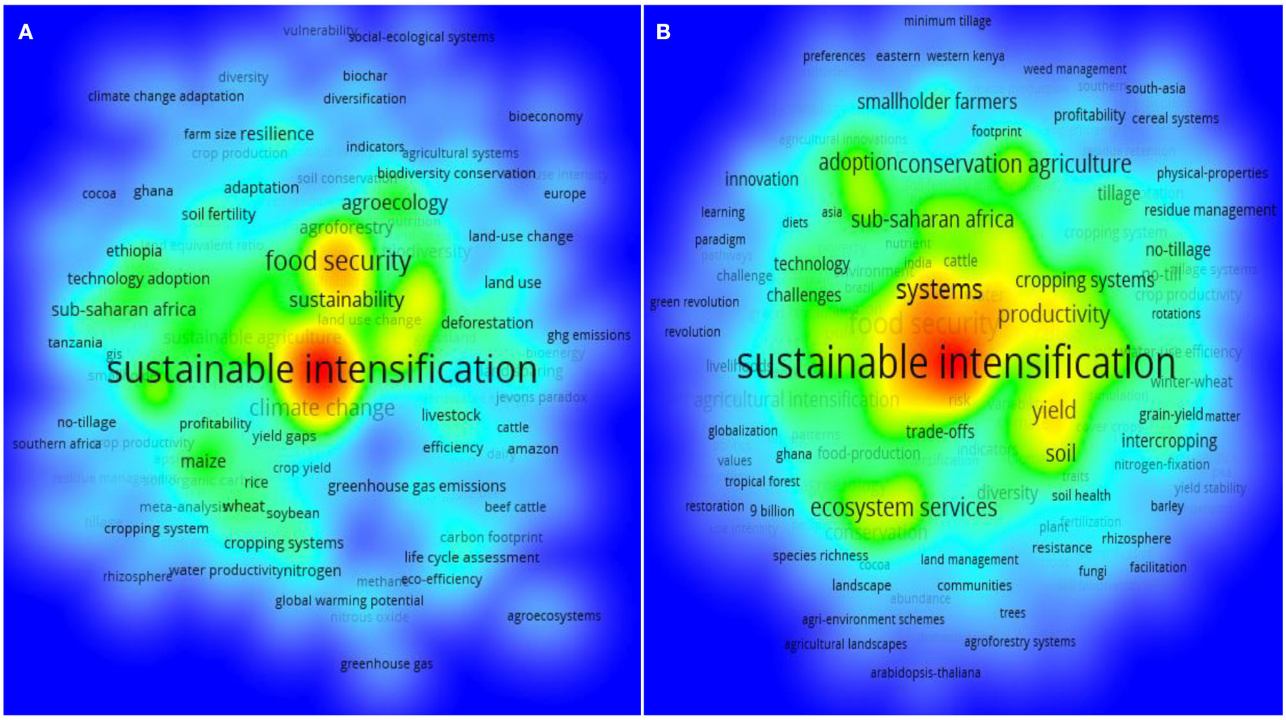

FIGURE 9
Author keywords (216) **(A)** and all keywords (611) network visualization **(B)** from 2010 to 20 August 2021.

7. Author and all keywords analysis

Apart from the first top keyword, which was the searching keyword ("Sustainable Intensification") in the present study, the second-ranking keyword in both author and all keywords is "Food Security", with 140 and 276 occurrences. Under author keywords, "Food Security" was followed by, "Agriculture" with 75, "Climate Change" with 75, "Sustainability" with 68, "Ecosystem Services" with 67, "Conservation Agriculture" with 54, "Agroecology" with 44, and "Sustainable Agriculture" with 43 occurrences, respectively. After "Sustainable Intensification" and "Food Security" in all keywords, "Management" (272), "Agriculture" (255), "Systems" (208), "Ecosystem services" (164), "Climate change" (158), "Conservation Agriculture" (145), "Productivity" (133), and "Yield" (133) was in the top 10 with more than 130 occurrences. It is worth noting that keywords like "Food Security", "Climate Change", "Agriculture", "Ecosystem Services", "Sustainability", "Conservation Agriculture", "Sub-Saharan Africa", "Maize", and "Intensification" appeared in both the top 20 author keywords and all keywords as shown in Table 3.

8. Co-authorship and organizations

Analysis of organizations involved in the SI field can assist in realizing the collaboration potential and capacity of organizations around the world, including the most productive organizations. The density visualization was selected to understand the most dominant organizations on the map (Figure 10B). Based on Chawla and Davis (2013), density visualization is used to understand the map's general structure and important areas. For instance, the map's red and yellow color shows the most dominant organizations. *Wageningen University* was the most productive organization, with 155 publications. Even with TLS of 419 (Table 4), Wageningen University was in the same cluster as CSIC, CSIR, the International Institute of Tropical Agriculture, and the University of Free State (Figure 10A), suggesting the dimension of similarity between the organizations. The second-ranking organization was the International Maize and Wheat Improvement Center (137), which was followed by the International Institute of Tropical Agriculture (69), *Michigan State University* (53), China Agricultural University (42), and the University of Minnesota with 34 publications. Even though the University of Minnesota was not among the top 6 most productive organizations in terms of publication output, the university had the highest number of citations (6,936) after Wageningen University. It is worth noting that out of 1,981 organizations involved in the SI field from 2010 to 2021, only 216 met a minimum of five publications and were grouped in 13 clusters.

9. Frequently cited documents

The literature highlighted that when the field of study is being evaluated, the citation obtained by the document should be considered, as it is necessary (Carrión-Mero et al., 2020). The papers involved in this research were cited 40 409 times, with an average citation of 25.1 per paper and an h-index of 85. Based on the *h*-index, which is used to measure the citation impact and the productivity of the publications, the *h* index of 85 indicates that 85 publications have more than 85 citations. The top 15 most cited publications in SI are shown in Table 5.

TABLE 3 Top 20 authors and all keywords' occurrences in SI research from 2010 to 20 August 2021.

RO	Author keyword	Occurrences (%)	All keywords	Occurrences (%)
1	Sustainable intensification	437	Sustainable intensification	838
2	Food security	148	Food security	290
3	Agriculture	75	Management	272
4	Climate change	75	Agriculture	255
5	Sustainability	68	Systems	208
6	Ecosystem services	67	Ecosystem services	164
7	Conservation agriculture	54	Climate-change	158
8	Agroecology	44	Conservation agriculture	145
9	Sustainable agriculture	43	Productivity	133
10	Maize	31	Yield	133
11	Biodiversity	30	Intensification	118
12	Intensification	30	Biodiversity	115
13	Intercropping	30	Adoption	110
14	Africa	29	Impacts	105
15	Sub-Saharan Africa	29	Nitrogen	101
16	Agricultural intensification	28	Soil	100
17	Resilience	26	Sub-Saharan Africa	97
18	Yield gap	25	Maize	91
19	Agroforestry	24	Sustainability	89
20	Smallholder farmers	24	Land-use	88

RO, ranking order.

The most cited publication with 2,952 citations, entitled "Global food demand and the SI of agriculture," was published by Tilman et al. (2011) from the United States of America. In their study, the researchers promoted the adoption of Sustainable Agricultural Intensification. In the same study, the authors noted that the intensification of agriculture through transfer, improvement of soil fertility and technology adoption in poorer countries would greatly reduce yield gaps, provide a more equitable supply of food, greatly decrease greenhouse emissions and the extinction of species from land clearing. The second most cited paper published by Ray et al. (2013) is entitled "Yield Trends Are Insufficient to Double Global Crop Production by 2050," with 1,235 citations. The authors identified areas where investment is needed to increase crop production and yield improvement and is on track to double crop production. The authors found that SI in Africa and elsewhere is necessary and possible to boost global crop production (Pretty et al., 2011; Mueller et al., 2012). The third most cited publication with 1,232 citations is "Closing yield gaps through nutrient and water management." The co-authored paper was published in 2012 by Mueller et al. The authors investigated efforts required to increase yields on underperforming agricultural landscapes. The authors pointed out that one strategy for meeting food security and sustainability while decreasing agriculture's environmental global footprint is to increase resource use efficiency. The rest of the publications in the top 15 have <1,000 citations (Table 5).

10. Discussion

The first three papers were published in 1997 by Pretty, Bebbington, and Reardon et al., under the topic "Social capital and rural intensification: local organizations and islands of sustainability in the rural Andes, "Promoting sustainable intensification and productivity growth in Sahel agriculture after macroeconomic policy reform," and "The sustainable intensification of agriculture." All three papers are connected to the promotion of SI, where there are existing opportunities for its adoption. However, an increase in the number of publications in 2011 shows that the inclusion of SI in agricultural and environmental policies was a success, and its adoption was gaining more recognition. For example, the first three most cited papers in the present study (Tilman et al., 2011; Mueller et al., 2012; Ray et al., 2013), each with more than 1,000 citations, agree that the SI of agriculture is required to meet the global food demands of 2050, rather than agricultural land clearing, and this includes studies by Garnett et al. (2013) and Vanlauwe et al. (2014). Also, a more recent study under the list of most cited articles (Table 5) by Rockström et al. (2017) suggests that sustainable transformation of agricultural systems is urgently and directly required to meet the Earth and World demands. The same authors are of the view that one strategy to be used "is the investment in spatially concentrated major grand experiments" where the knowledge from different domains, ranging from irrigated to rain fed agriculture, equity to business development, ecology and agronomy, work together to pilot SI at scale (e.g., in

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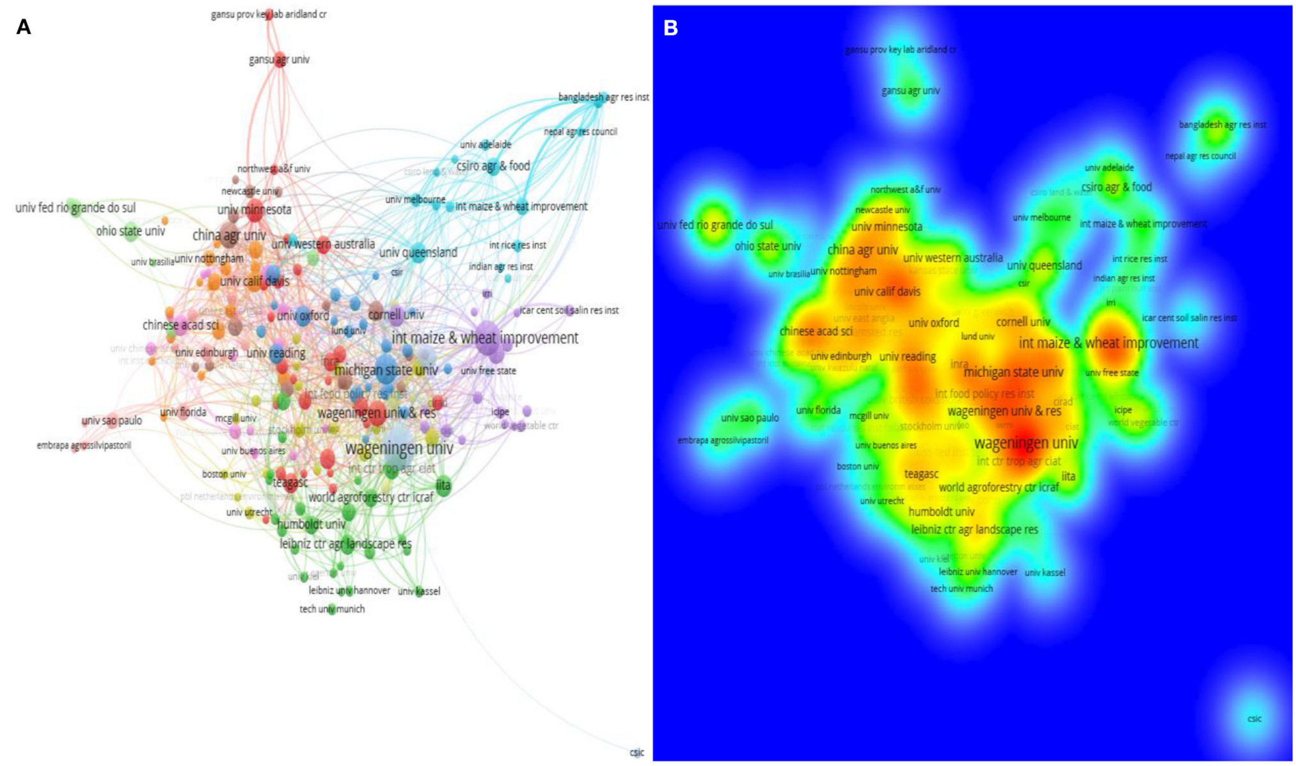

FIGURE 10
The network visualization **(A)**, and density visualization **(B)** of co-authorship by the organization from 2010 to 20 August 2021.

TABLE 4 Top 10 most productive organizations in the SI research field from 2010 to 2021.

RO	Organization	TLS	RC	Citations
1	Wageningen University	419	155	3,967
2	Int Maize & Wheat Improvement Ctr	203	137	2,754
3	International Institute of Tropical Agriculture	194	69	1,578
4	Michigan State University	71	53	1,474
5	China Agricultural University	47	42	1,090
6	University of Minnesota	90	34	6,936
7	Cornell University	35	29	501
8	Chinese Academy of Science	62	26	506
9	University of Queensland	128	26	389
10	University of California, Davis	106	25	1,402

RO, ranking order; TLS, total link strength; RC, record count.

a region or basin), to pool experience, explore synergies and trade-offs, testing the hypothesis that SI can deliver livelihoods, food, and resilience while also contributing to development within Earth's safe operating space."

The USA has contributed most to the SI research based on publications, followed by England. The highest number of publications in the US and European countries shows that publications on the topic are concentrated in developed countries, indicating that these developed countries play a crucial role in the SI of agriculture. The position of Kenya as the only African country in the top 10 can be explained by the availability of funding from CGIAR (45 publications), followed by the United States Agency for International Development/USAID (18 publications), European Commission (16 publications), Bill & Melinda Gates Foundation (10 publications) and Australian Centre for International Agricultural Research (six publications), and its association with the following organizations; GCIAR (102 publications; 64.96%); International Livestock Research Institute (42; 26.75%), Wageningen University Research (21.02%), World Agroforestry ICRAF (19.11%), and Alliance (29; 18.48%), respectively. Additionally, the earlier promotion of the SI field in Kenya after England, as shown in Figure 8, and the close interactions between Kenya and European countries like the Netherlands and France, can explain its position.

The use of overlay visualization to show the earliest and most recent publications has shown that the country with recent publications has the lowest number of publications, with fewer collaborations. A typical example is Uruguay, with 13 publications and 11 links. The lowest contribution can be attributed to the late adoption of SI in the country, where SI was included as one of the five strategic public policy approaches for 2015 to 2020 to achieve a sustainably intensified and Agro-Smart agricultural sector (World Bank; CIAT, 2015). The results show that SI is one of the important monasteries in European Agriculture. For instance, the highest contribution of the EU countries to SI research is likely due to the decision made by the EU to push for SI in European agriculture without degrading the environment (Fischler and Pirzio-Biroli, 2014).

TABLE 5 Top 15 most cited documents about SI.

RO	References	Research paper	Citations
1	Tilman et al. (2011)	Global food demand and the sustainable intensification of agriculture	2,952
2	Ray et al. (2013)	Yield trends are insufficient to double global crop production by 2050	1,235
3	Mueller et al. (2012)	Closing yield gaps through nutrient and water management	1,232
4	Garnett et al. (2013)	Sustainable intensification in agriculture: premises and policies	778
5	Van Ittersum et al. (2013)	Yield gap analysis with local to global relevance-A review	713
6	Pittelkow et al. (2015)	Productivity limits and potentials of the principles of conservation agriculture	552
7	Pretty et al. (2011)	Sustainable intensification in African agriculture	513
8	Godfray and Garnett (2014)	Food security and sustainable intensification	412
9	Brooker et al. (2015)	Improving intercropping: a synthesis of research in agronomy, plant physiology and ecology	363
10	BajŽelj et al. (2014)	Importance of food-demand management for climate mitigation	330
11	Linquist et al. (2012)	An agronomic assessment of greenhouse gas emissions from major cereal crops	325
12	Rockström et al. (2017)	Sustainable intensification of agriculture for human prosperity and global sustainability	300
13	Smith et al. (2016)	Global change pressures on soil from land use and management	288
14	Pretty and Bharucha (2014)	Sustainable intensification in agricultural systems	284
15	Fischer et al. (2014)	Land sparing versus land sharing: moving forward	277

RO, ranking order.

Additionally, the urge to move toward SI might be because most of the existing intensively farmed land in Europe is not managed sustainably, as noted by Buckwell et al. (2014). From the study by Schiefer et al. (2016) entitled "potential and limits of land and soil for SI of European agriculture," the suitability and the potential of land and soil for SI were explained after the area of arable land was analyzed by FAO Stat-Agricultural area in 2015. In their study, some European union member countries with very low contributions in the SI field, like Slovakia, Slovenia, and Hungary, were included. From their findings and recommendations, after Luxembourg and Belgium, the soil in Slovakia has high resilience and is suitable and recommended for SI. For instance, of the 96% area of arable land (13,376 km^2) analyzed, 76.9% is highly resilient and recommended for SI. In the case of Hungary and Slovenia, of the 94% (40,657 km^2) and 25% (433 km^2) area of arable land analyzed, 62.3 and 34.2% were highly soil resilient and recommended for SI. Therefore, researchers should take advantage of these soils by adopting more sustainable ways of farming, especially in countries like Hungary, where there is potential for corn production and where corn production is vulnerable in the long run (Marton et al., 2020). Also, both fertilizers and pesticides in highly resilient soils can be transformed into performance, while their application in low resilient soils usually leads to environmental pollution (e.g., groundwater). Based on Blum (1994), soil resilience is the capacity of a system to return to a new equilibrium after disturbance, and it defines the arable land's potential sustainable agricultural production and, consequently, the limits for SI (Buckwell et al., 2014).

The occurrence of agro-ecology in author keywords can be linked to the fact that agro-ecology is presented as a component of SI and CSA [Global Alliance for Climate-Smart Agriculture (GACSA), 2014], even though it is in other countries' aspects different from CSA. In a research paper published by Sahu et al. (2020) under the topic "Climate-Smart Agriculture: A new approach for sustainable intensification," the authors stated that CSA and SI are complementary and play a significant role in fighting global warming, nutrition, and food security. Therefore, the global adoption of CSA and SI practices is crucial for meeting global food demand that is projected to increase in the face of climate change and environmental land degradation. Out of thousands of crops available globally, "maize" as a grain crop occurred in both author and all keywords (Table 3) as the widely grown crop, especially by smallholder African countries as a staple crop. From the top 10 list of most productive co-authors, three authors are working for the International Maize and Wheat Improvement Center (CIMMYT), including Jat, M. L, Baudron Frederic Thierfelder Christian. For instance, Jat ML from India leads CIMMYT's climate-smart agriculture research portfolio in South Asia as part of CGIAR, regularly coordinating and providing strategic support to CIMMTY's sustainable intensification efforts to mobilize resources for scaling SI and CSA in wheat and maize systems. These authors are based in developing countries like India, Zimbabwe, which shows that SI is key to agricultural development in Asia and Africa.

On the other hand, the occurrence of other keywords like "food security," "climate change," "agriculture," "ecosystem services," "conservation agriculture," "Sub-Sahara Africa," "Africa," and "Biodiversity" in both author and all keywords reveals the significance of sustainable intensification (SI) in African Agriculture, in the face of climate change and food insecurity, and the promotion of biodiversity after its adoption by the farmers. The number of publications produced should also analyze the importance of SI in African countries, and currently, only a few African countries have contributed to the field, even though the term SI was initially used in the context of African smallholder agriculture in the mid-1990s (Pretty, 1997; Garnett and Godfray, 2012), with farmers as research objects and their behavior choices in the practice of SI (Kassie et al., 2015; David et al., 2016). Sub-Saharan countries like South Africa, Ethiopia, Tanzania, Ghana, and Zimbabwe were among the top 30 countries in the SI research, contributing 18.82% (303 publications).

In Sub-Sahara Africa, about 24% of the land area is affected by land degradation, with an estimated economic loss of about 68 billion dollars per annum and about 180 million people. While 12% of South Africa's landmass is suitable for arable production, only 3% of the land is genuinely fertile.

Nevertheless, despite the great potential of SI practices in Africa, further work to support improved extension messages and consider the wide range of practices needed for sustainable, integrated crop management is required. Also, for African smallholders, agricultural intensification, whether ecological, sustainable, or conventional, is simply a necessity (Tittonell and Giller, 2013). However, the implementation of SI is complicated by temporal delays in yield increase and positive returns, including limited supportive policy frameworks for sustainable agriculture, as reported by Pretty (2008) and Petersen and Snapp (2015).

11. Conclusions

Most contribution mainly focuses on sustainable agricultural practices which are designed to promote food security in Sub-Saharan African countries. Even though the focus was on African countries, the contribution from African scholars was significantly lower. With Kenya being the most contributing country in Africa, funding and research opportunities throughout Africa can help promote food security in the region. Opportunities for more sustainable agricultural practices are not restricted to Sub-Saharan and African nations, where food security and nutrition are threatened by the vulnerability of farmers to the effects of climate change, but also exist in European nations such as Slovakia and Hungary, where sustainable intensification (SI) has been recommended due to the high soil resilience of arable land.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

Conceptualization: SA and CB. Methodology, formal analysis, investigation, resources, writing—original draft preparation, and visualization: SA. Validation and writing—review and editing: SA, CB, BS, and MG. All authors contributed to the article and approved the submitted version.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Caught off guard and beaten: The Ukraine war and food security in the Middle East

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The Ukraine war has led to a severe global food crisis due to complex supply disruptions and price increases of agricultural inputs. Countries of the Middle East have been directly affected because of their high dependence on food imports from Russia and Ukraine. Furthermore, this food crisis comes at times of high baseline vulnerability due to the compound impacts of COVID-19, repeated food shocks, and weakened states due to political-economic difficulties. This paper provides a detailed analysis of the food-related vulnerability of Middle Eastern countries in the wake of the Ukraine war. It contextualizes the varying impacts of this crisis in the region, and highlights country-level response strategies. The analysis shows a concerning and deepened crisis in the case of highly exposed and politically fragile countries with weakened food sectors; e.g., Lebanon, Sudan, and Yemen. Political-economic instabilities, limited domestic agriculture, and the lack of reliable grain reserves have aggravated the current food crisis in some countries. At the same time, indigenous short-term responses related to regional aid and cooperation have emerged, particularly in the Gulf countries, which have witnessed soaring revenues from higher energy prices. Alongside more regional frameworks for collaboration on food security, future action to mitigate such food crises should include the strengthening of local sustainable agriculture, storage capacities, and grain procurement strategies from international suppliers.

KEYWORDS

food security, Middle East, Ukraine war, global food crisis, Russia, grain

1. Introduction

The Ukraine war marks a new era in international diplomatic and economic relations, with major anticipated reconfigurations of trade flows. Not only are the direct disruptions to production in violence-ridden areas a matter of concern, but the war has also been accompanied by sanctions and boycotts causing major value-chain disruptions. In fact, although the effects take time, trade has always been part of the collateral damage of wars, with significant associated costs (1, 2). Furthermore, war-related impacts such as decoupling from the global economy, imposed sanctions, and (to some degree) consumer-led boycotts can cause further trade damage (3, 4). In the case of the Ukraine war, the impacts on global trade and economic relations have been immediate in terms of downgraded global growth (estimated at 3.5% instead of the usual level of above 4% for 2022) (5). The consequences go far beyond the European continent as regions such as Latin America and Africa have felt the economic impact through inflated commodity prices and financial volatility (6, 7).

The long-term consequences for energy trade with Europe after the Ukraine war has been a key subject of debate. However, in the short term, the war has already resulted in serious food security concerns for highly vulnerable regions (8). It has immediately caused major risks and shortfalls; e.g., related to production, trade flows, and prices of food commodities, since Ukraine and/or Russia have been among the top three global producers of wheat, maize, rapeseed, sunflower seeds, and sunflower oil (9). Furthermore, Russia ranks very high globally in the production of key fertilizers (ibid.). Therefore, there have been dire warnings of food insecurities as a result of the Ukraine war. With less grain and fertilizer available due to the war, the global food supply is threatened. Between 2016 and 2021, Ukraine and Russia produced more than 50% of the world's supply of sunflower seed, 19% of the world's barley, and 14% of its wheat (10), while they accounted for ca. 30% of global wheat exports (11, 12). With at least 50 countries depending on Russia and Ukraine for 30% or more of their wheat supply, a global food crisis has been triggered, exacerbated by higher energy prices, as was also the case in the recent crises of 2007–2008 and 2010–2012 (13). The soaring energy prices affected fertilizer costs (natural gas is used in fertilizer production) and thus restrained local production worldwide, including in Europe (14–16). The Black Sea Grain Initiative (BSGI) signed in July 2022 to allow some grain exports from Ukraine has alleviated some impacts of the Ukraine war on food security, particularly easing pressures on markets for grains (17). However, as of January 2023, the BSGI is still fragile due to restrictions of shipments while an enduring global food crisis is still persistent (18).

The complexity of the food crisis caused by the Ukraine war necessitates detailed assessments of regional vulnerabilities. The Middle East is considered to be one of the worst-hit regions since several countries in the region are listed among the countries most dependent on agri-food commodities from Ukraine and Russia; e.g., in order of dependence, Turkey, Egypt, Sudan, Tunisia, Morocco, and Saudi Arabia (19). Other reports indicate that other countries such as Lebanon, Yemen, and Jordan are particularly vulnerable, and highlight special cases of existential threats; e.g., for Egypt (20). Within this focus on the repercussions of the Ukraine war on food security in Middle Eastern countries, there is a need to go beyond rapid assessments of past dependence to analyze the vulnerability contexts of these countries. This paper presents such a contextualization of the food security impacts of the Ukraine war. Here, food security is defined in accordance to the United Nations (UN) as all people, at all times having "physical and economic access to sufficient safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life" (21).

There is so far no knowledge regarding the impacts of the Ukraine war within the context of repeated shocks from COVID-19 and economic or political crises in the Middle East. To address this, this paper aims to provide a more detailed analysis of the vulnerability of the Middle East to food insecurity in the aftermath of the Ukraine war. It contextualizes this food crisis within country-level vulnerabilities and recent political-economic shocks. This paper's analysis focuses on access aspects to food in the wake of the Ukraine crisis, with an emphasis on stable crops. Through identifying high-risk countries and possible mitigation strategies, this paper shows the impacts of the food security crisis on Middle Eastern countries, and how these impacts happen at different speeds. It also illustrates indigenous adaptation pathways using intraregional cooperation mechanisms. While this paper focuses on access to stable crops, it does not tackle nutrition and dietary aspects; for example, it does not look into horticultural produce and animal-source food which are also imported into the Middle East.

2. Recurrent food supply shocks: from COVID-19 to the Ukraine war

In 2022, many developing countries, particularly those in Africa and the Middle East, have been shaken by the impacts of the COVID-19 pandemic. In this year, it is estimated – before the Ukraine war – that around 44 million people in 38 countries are threatened by hunger (22). In the Middle East and North Africa, the number of food-insecure people has increased dramatically, with one in three people in 2020 with no access to adequate food, an increase of 10 million people from 2019 (23). Besides COVID-19, several countries in the Middle East (defined broadly in this paper to include countries of the Arab League as well as Turkey and Iran) are suffering from protracted conflicts (e.g., Yemen, Syria, Libya), increased political instability (e.g., Lebanon, Sudan, and Tunisia), or the aftermath of hard economic reforms (e.g., the impacts of structural reforms in Egypt). The Middle East has been one of the world's major cereal-importing regions, particularly of wheat, while food supply problems – limited yields or increased prices–of grain such as wheat from Ukraine and Russia have historically affected food security in this region (24). For example, interruptions of grain exports from Russia, Ukraine or Kazakhstan due to harvest failure or export restrictions immediately resulted in soaring costs for the food subsidy systems in major dependent countries (25).

Meanwhile, the negative impacts of the COVID-19 crisis on food security in Middle Eastern countries have been well-documented in the academic literature. COVID-19 has resulted in serious disruptions to the food value chain, with grain export restrictions during the pandemic, together with locusts destroying crops and causing price hikes, and food insecurity across many regions including parts of the Middle East (26). Countries located in the Sahel region have been particularly vulnerable during the pandemic, with COVID-19 resulting in weakened food sectors (27). COVID-19 has forced a re-evaluation of the water–food–trade link within the water–energy–food nexus, and reignited debates regarding self-sufficiency and the expansion of the local food production, even in arid regions (28). COVID-19 might have increased isolationist voices in many of the world's regions, in contrast to voices advocating for the strengthening of the resilience of international trade. However, self-sufficiency in food products is an illusionary strategy in the arid region of the Middle East, and past strategies in this regard–e.g., in countries of the Gulf Cooperation Council (GCC) – have failed (29).

Prior to COVID-19 and the current Ukraine-related crisis, the Middle East had only recently emerged from years of recurrent food shocks. Early this century, Middle Eastern countries suffered from unreliable imports and began investing in reserves and the acquisition of foreign agricultural land (30, 31). Moreover, many countries of the region (e.g., Syria, Yemen, South Sudan, and Somalia) have suffered from serious conflict-related economic shocks, thus jeopardizing food and nutrition security (32). As an additional aggravator of baseline food supply vulnerability, climate-related shocks are causing food insecurity. In particular, several types of droughts (hydrological, meteorological, and agricultural) have affected the performance of the food sectors in the Middle East in recent decades (33). With the earlier-mentioned impacts of COVID-19, in the year 2021, serious supply bottlenecks existed, with the price of wheat and barley increasing by 31%, and rapeseed oil and sunflower oil by more than 60% (12). These factors combined indicate an alarming trend of increased vulnerability of food supply systems in the Middle East, which has been aggravated by the Ukraine crisis, thus bringing the region close to a worst-case scenario of food insecurity. The BSGI seems to have avoided this worst-case scenario for the Middle East and North African (MENA) region since the region has received a significant amount of the grain exports under this deal, e.g., 42% of Ukrainian grain exports between August and October 2022, and 28% of its corn exports for the same period (34). However, the faith of the BSGI was uncertain in late 2022 as Russia threatened to leave the agreement and still restricted some shipments in early 2023 (18). Any halt of the BSGI would severely set back progress toward mitigating the food crisis in the Middle East (35). Besides, the level of imports from Ukraine in 2022 was far below the 2021 level for the important grain of wheat (34). In fact, as of January 2023, 17.8 million tons of grains were shipped from Ukraine, of which 46% were corn and 28% wheat, with China, Spain, Turkey, Italy, and the Netherlands as the main destinations (36). Therefore, the BSGI is geared toward containing prices and stabilizing markets rather than averting famine (17). As this paper will explain in the next sections, the repercussions of the Ukraine crisis on the Middle East's food security have been profound in 2022 and with far-reaching impacts beyond.

3. Methodology and data

In order to assess and contextualize the food-related vulnerabilities of Middle Eastern countries in the wake of the Ukraine water, the analysis in this paper is carried out in two steps. Firstly, the relative level of vulnerability to supply risks from Ukraine and Russia is determined. For this, trade data obtained from UN Comtrade are initially used (aggregated for the last five years, 2016–2020) to determine the biggest importers from Russia and Ukraine in key food commodity categories, and also to determine dependence levels of Middle Eastern countries on imports from Russia and Ukraine in some important food commodity categories. Later, in order to categorize the vulnerability of Middle Eastern countries, the dependence indicators are combined with data from the Global Food Security Index (GFSI) published by the Economist. The GFSI is a composite index using indicators in four categories: affordability, availability, quality and safety, and natural resources and resilience. In our analysis, the data provided by the GFSI on the baseline vulnerability of Middle Eastern countries to increased risks due to the Ukraine war, together with the dependence indicators, allow information to be extracted on which Middle Eastern countries are particularly vulnerable during this crisis.

Secondly, using the categorization of Middle Eastern countries in terms of relative vulnerability related to the food insecurity crisis caused by the Ukraine war, a country-level case analysis is carried out. For this, the paper uses the recent academic literature, announcements from international organizations, and media reports on country-level adaptation measures in order to present the vulnerability contexts at the country level. As for academic literature on the impacts of the Ukraine crisis on food security in the Middle East, this study does not present a full literature review due to the lack of studies on this recent topic. For example, a scopus-based search was conducted in January 2023 using the keywords "food security" and "Ukraine" in either in the title, abstract or keywords of the publications, together with any of the following keywords: Middle East, MENA, North Africa or the country name (see **Table 2**). The resulting dataset was only 11 documents, 7 of which from 2022 or later, and only 3 on a Middle Eastern country (2 on Lebanon and 1 on the UAE). This small number of papers was used in the analysis, but it largely relied on earlier studies known to the author on the vulnerability context, and the earlier-described types of documents available through online search related the current conflict. Together, these studies and documents elaborate the contexts that are related to the performance of the local food sector in response to the recent food-related shocks. In addition, through analyzing the cases, a particular emphasis is placed on required actions and short- to medium-term adaptation strategies to be carried out by the Middle Eastern countries and through the mechanisms of regional or international cooperation. Such an analysis is later synthesized into larger regional lessons learnt from contextualizing the current crisis within recent developments affecting vulnerability in the Middle East due to compounded health and political-economic shocks.

4. Results

4.1. Assessing baseline vulnerability and food dependence

In order to determine the vulnerability of Middle Eastern countries to the current shock related to the Ukraine war, one needs to assess the relative importance of any potential disruptions in the components of the food value chain related to Ukraine and Russia. Firstly, the importance of food trade between Russia, Ukraine, and the Middle East can be shown using key categories of food commodities. **Table 1** shows the biggest importers from Russia and Ukraine in the last 5 years (2016–2020), identifying some Middle Eastern countries as important trade partners of Russia and Ukraine. Egypt ranks highly as the biggest importer of cereals from both Ukraine and Russia, with a trade volume of more than 12 billion USD between 2016 and 2020. Turkey is also a key trade partner, particularly with regard to cereals, oil seeds, fats, and oil. Other Middle Eastern countries rank highly only in certain categories; notably, Iraq's imports of fats and oil from Ukraine, or the UAE's imports of milled products from Ukraine. In the category of cereals, ca. 30% of the trade value of Ukraine's exports stems from eight Middle Eastern countries (Egypt, Turkey, Saudi Arabia, Tunisia, Israel, Libya, Iran, and Morocco). The top eight Middle Eastern countries for cereal exports from Russia (Egypt, Turkey, Iran, Saudi Arabia, Sudan, Yemen, Lebanon, and the UAE) account for ca. 40% of the total value of these exports between 2016 and 2020.

While the value of food exports from Russia and Ukraine to some countries might be relatively small, imports from Ukraine and Russia can still be high in terms of total imports. **Table 2** shows the import dependence ratios of Middle Eastern countries from Russia

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TABLE 1 The biggest importers of key food commodity categories from Ukraine and Russia (2016–2020).

Rank[a, b]	Cereals[1]		Milling industry[2]			Oil seeds[3]			Fats and oil[4]		
Biggest importers from UKRAINE 2016–2020 (amount in billion USD included after country name)											
Total	World	38.87	Tot	World	0.86	Tot	World	9.96	Tot	World	23.56
1	Egypt	4.69	**1**	China	0.08	**1**	Turkey	1.65	**1**	India	7.43
2	China	4.18	**2**	Rep. of Moldova	0.07	**2**	Germany	1.48	**2**	China	3.32
3	Spain	2.86	**3**	United Arab Emirates	0.07	**3**	Belgium	1.14	**3**	Netherlands	1.91
4	Netherlands	2.35	**4**	Angola	0.06	**4**	Netherlands	0.85	**4**	Spain	1.61
5	Indonesia	2.23	**5**	Israel	0.04	**5**	Egypt	0.78	**5**	Italy	1.29
6	Turkey	1.63	**6**	Indonesia	0.04	**6**	France	0.55	**6**	Iraq	0.95
7	Bangladesh	1.52	**7**	State of Palestine	0.04	**7**	Belarus	0.51	**7**	Poland	0.78
8	Italy	1.38	**8**	Poland	0.03	**8**	Iran	0.44	**8**	France	0.52
9	Saudi Arabia	1.38	**9**	Singapore	0.03	**9**	Poland	0.41	**9**	Iran	0.51
10	Tunisia	1.38	**10**	Brazil	0.02	**10**	Italy	0.26	**10**	Egypt	0.41
11	Israel	1.24	**11**	Somalia	0.02	**12**	Lebanon	0.22	**13**	Turkey	0.37
12	Libya	1.14	**14**	Turkey	0.01	**14**	Israel	0.14	**14**	United Arab Emirates	0.34
14	Iran	1.1	**15**	Egypt	0.01	**18**	United Arab Emirates	0.09	**15**	Saudi Arabia	0.22
15	Morocco	0.97	**18**	Saudi Arabia	0.01	**27**	Algeria	0.02	**16**	Lebanon	0.22
20	Lebanon	0.6				**29**	Tunisia	0.02	**19**	Jordan	0.14
22	Algeria	0.49							**20**	Sudan	0.12
25	Yemen	0.39							**23**	Oman	0.12
28	Jordan	0.23							**25**	Israel	0.08
31	Mauritania	0.17							**33**	State of Palestine	0.05
38	United Arab Emirates	0.12							**37**	Qatar	0.04
									57	Djibouti	0.02
43	Sudan	0.01							**65**	Kuwait	0.02
46	Djibouti	0.01							**69**	Yemen	0.02
47	Qatar	0.01							**79**	Syria	0.01
50	Oman	0.01							**92**	Bahrain	0.01
53	Kuwait	0.01									

(Continued)

TABLE 1 (Continued)

Rank[a, b]	Cereals[1]		Milling industry[2]			Oil seeds[3]			Fats and oil[4]		
Biggest importers from RUSSIA 2016–2020 (amount in billion USD included after country name)											
Total	World	40.82	Tot	World	1.42	Tot	World	4.58	Tot	World	14.92
1	Egypt	7.4	**1**	Norway	0.17	**1**	China	1.61	**1**	China	2.47
2	Turkey	6.09	**2**	China	0.16	**2**	Turkey	0.74	**2**	Turkey	1.79
3	Bangladesh	1.91	**3**	Belarus	0.13	**3**	Belarus	0.55	**3**	Egypt	1.03
4	Iran	1.79	**4**	Kazakhstan	0.1	**4**	Belgium	0.36	**4**	Iran	0.96
5	Saudi Arabia	1.68	**5**	USA	0.09	**5**	Bulgaria	0.17	**5**	Uzbekistan	0.84
6	Sudan	1.32	**6**	Turkey	0.07	**6**	Kazakhstan	0.14	**6**	Kazakhstan	0.8
7	Nigeria	1.29	**7**	Uzbekistan	0.06	**7**	Latvia	0.13	**7**	Norway	0.79
8	Azerbaijan	1.16	**8**	Ukraine	0.06	**8**	Poland	0.11	**8**	Algeria	0.75
9	Viet Nam	1.07	**9**	Azerbaijan	0.06	**9**	Mongolia	0.11	**9**	India	0.58
10	Yemen	1.05	**10**	Georgia	0.06	**10**	Germany	0.09	**10**	Belarus	0.53
11	Lebanon	0.84	**24**	Israel	0.01	**12**	Iran	0.06	**13**	Sudan	0.25
12	United Arab Emirates	0.71	**25**	United Arab Emirates	0.01	**21**	Egypt	0.02	**15**	Saudi Arabia	0.23
15	Israel	0.61	**29**	Syria	0.01				**18**	Lebanon	0.21
20	Jordan	0.52							**26**	Tunisia	0.13
22	Morocco	0.47							**30**	Israel	0.07
23	Libya	0.45							**32**	Syria	0.06
26	Oman	0.36							**37**	Morocco	0.03
42	Syria	0.15							**44**	Jordan	0.02
51	Qatar	0.12							**46**	United Arab Emirates	0.01
61	Algeria	0.01							**49**	Oman	0.01
62	Mauritania	0.01									
69	Kuwait	0.01									
73	Djibouti	0.01									

(a) All data represent values of Russian exports to indicated countries in billion USD. The food commodity category are as follows: (1) Cereals = Commodity Code 10: Cereals; (2) Milling industry = Commodity Code 11: Products of the milling industry; malt, starches, inulin, wheat gluten; (3) Oil seeds = Commodity Code 12: Oil seeds and oleaginous fruits; miscellaneous grains, seeds and fruit, industrial or medicinal plants; straw and fodder; (4) Commodity Code 14 = Animal or vegetable fats and oils and their cleavage products; prepared animal fats; animal or vegetable waxes.
(b) All data retrieved from the UN Comtrade Database at https://comtrade.un.org/data/.

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TABLE 2 Import dependence of Middle Eastern countries from Russia and Ukraine (2016–2020) in key food categories.

Country[a,b]	Import dependence ratios from Ukraine (U) and Russia (R) total imports value in billion USD dollar (Tot) and percentage from U or R (%)											
	Cereals (Tot)	Cereals%		Milling industry (Tot)	Milling industry%		Oil seeds (Tot)	Oil seeds%		Fats and oil (Tot)	Fats and oil%	
		R	*U*		*R*	*U*		*R*	*U*		*R*	*U*
Algeria (16–17)	5.5	1.20%	2.70%	0.05	0.90%	0.02%	0.05	0.90%		1.6	23%	5%
Bahrain (16–19)	0.4	0.10%	0.20%	0.0081	0.01%	0.16%	0.05%	0.70%	0.20%	0.182	0.10%	1.10%
Egypt (16–20)	23	34%	24%	0.163	0.10%	6%	7.9	0.30%	12%	6.4	14%	4.40%
Iran (16—18)	10.6	7.30%	3.20%	0.02%	NA	6.50%	4.4	1%	3.70%	3.2	12%	9%
Israel (16–20)	4.4	8%	16%	0.4	2%	6%	1.9	0.10%	3.20%	0.9	4%	6%
Jordan (16–20)	3.9	14%	7.40%	0.1	0.30%	0.50%	0.6	0.30%	0.50%	0.89	2.20%	20%
Kuwait (16–20)	2.9	2.60%	1.70%	0.024	0.10%	0.40%	0.25	0.10%	0.40%	0.26	0%	1%
Lebanon (16–20)	1.6	22.60%	30.40%	0.17	0.09%	5.20%	0.485	0.02%	4.30%	0.7	16%	30%
Libya (16–18)	1.8	15%	35%	0.09	NA	4.30%	0.07	NA	4%	0.74	NA	1.40%
Mauritania (16–20)	0.9	14.50%	19.80%	0.01	NA	NA	0	NA	NA	0.06 (R); 0.16 (U)	0.01% [8]	0.08% [9]
Morocco (16–20)	8.7	5.50%	13.40%	0.02 (R); 0.08 (U)[10]	0.19%	2%	0.911	0.30%	1.50%	1.8	1.80%	1.40%
Oman (16–18)	1.3	14%	1.50%	0.0412	0.03%	6.50%	0.0213	0%	0.20%	0.2314	3.60%	6.80%
Qatar (16–20)	1.4	10.40%	7.80%	0.115	0.30%	3.10%	0.0716	0.04%	0.20%	0.5 (R);0.09 (U)[17]	0.07%	7.80%
Saudi Arabia (16–20)	17	7%	7%	0.23 (R);1.14 (U)[18]	0.09%	0.50%	0.93 (R); 4.2 (U)[19]	0.03%	0.06%	4.3	4.60%	5.10%
State of Palestine (16–20)	0.63	3.80%	0.60%	0.32	1.30%	33%	0.0921	0.13%	0.17%	0.25	2.70%	20.70%
Sudan (16–18)	2.422	76%	1.70%	0.423	7.30%	0.20%	0.07	NA	NA	0.7	23%	19%
Tunisia (16–19)	3.2	5.60%	40%	0.0224	0.04%	0.90%	0.925	0%	1.30%	0.9	15%	5%
Turkey (16–20)	12.5	51%	12%	0.64	11%	3%	10.3	9%	17%	7.3	30%	6.30%
United Arab Emirates (16–20)	6.1	10%	1.30%	0.6	0.17%	3.90%	4.95	0.02%	1.75%	2.8	0.50%	11%
Yemen (18–19)	1.5	20.60%	10.60%	0.18	NA	NA	0.02	NA	NA	0.08	NA	0.77%

(a) The years for calculated averages indicated after country name; e.g., 16–20 for years 2016–2020. If the years for the available data differ from the given years after the country name, this is indicated through number annotation as follows: [1] 2016 only; [2] 2017–2019; [3] 2016, 2017, 2019, and 2020; [4] 2020 only; [5] 2018–2020; [6] 2017 only; [7] 2018 only for Russia, and 2020 only for Ukraine; [8] 2018 only; [9] 2020 only; [10] 2019 only for Russia and 2016–2020 for Ukraine; [11] 2018–2020; [12] 2016 only; [13] 2016 only; [14] 2017 only; [15] 2016–2018; [16] 2016–2017; [17] 2020 only for Russia and 2016–2020 for Ukraine; [18] 2020 only for Russia and 2016–2020 for Ukraine; [19] 2020 only for Russia and 2016–2020 for Ukraine; [20] 2016–2019; [21] 2019–2020; [22] 2017–2018; [23] 2016–2017; [24] 2019 only; [25] 2017–2019.

(b) All data retrieved from the UN Comtrade Database at https://comtrade.un.org/data/.

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and Ukraine using the value of these imports (data based on trade quantities largely not available). The data shows some dependence ratios of concern for several Middle Eastern countries, particularly in the categories of cereals and fats and oil. Note that data from some countries (Iraq, Djibouti, Syria, and Somalia) were not available, while some countries did not report consistent data for the period 2016–2020, or reported only the total values of all imports. Therefore, dependency ratios were calculated for the indicated years only, and a high dependence should only be assumed in the case of availability of data for several years and/or existence of high ratios across several indicators.

Tables 3, 4 seek to contextualize the dependence ratios by including a multi-dimensional food security factor to approximate the ability of a highly dependent Middle Eastern country to accommodate a supply interruption shock from Ukraine and/or Russia. This factor is represented by the Global Food Security Index (GFSI), which can indicate short- to mid-term food sector performance, and thus gives some information about the baseline vulnerability of a country. In determining this vulnerability to the Ukraine war shock, this paper combines the dependence ratios with the GFSI scores (Table 4). Here, countries with dependence ratios below 10% in all categories are not considered vulnerable: i.e., Bahrain and Kuwait. The Group 1 countries show some level of vulnerability that is not necessarily threatening due to a low level of dependence (10–20%) and/or quite high food sector performance (GSFI above 75%). This paper will focus on the case study analysis on Groups 2–3 of moderately to highly vulnerable countries, which indicate dependence ratios of above 20%, together with a poorly developed food sector (GFSI below 75%). In addition, Group 4 of special cases will be mentioned in the discussion of the results but not analyzed in detail.

4.2. Moderately vulnerable countries: Political-economic context and state-led responses

4.2.1. "Manageable" pressures and balanced responses: Algeria, Jordan, and Turkey

The group of moderately vulnerable countries contains some Mediterranean countries with relative resilience and varying levels of dependence on imports from Ukraine and Russia. The level of dependence on Ukraine's agricultural exports matters more since it has become a main war area. This can divide Group 2 countries into two subgroups, with Algeria, Jordan, and Turkey forming the first group with "manageable" pressures, since their dependence levels are not very high and rather skewed toward Russia rather than Ukraine. In this category, Algeria has a concerning (more than 20%) dependence on Russia only in the category of oils and fats. As a result of the Ukraine war, Algeria has suffered from double-digit inflation, particularly hitting food staples whose prices were liberalized in 2021 through the removal of food and energy subsidies (37). However, the inflation and the removal of the food subsidies have been common to other Middle Eastern countries. Recently, some food subsidies were replaced with social safety programs in Egypt, Mauritania, Algeria and Sudan, and these programs targeting the poor can mitigate some of the potential impacts of the Ukraine war (9). Besides, Algeria does not show dependence on Russia or Ukraine regarding grain, which is imported from France (38). Algeria, the third largest wheat importer in the world, has for a long time disallowed the import of Russian wheat (39). Furthermore, as a significant gas-exporting country, rising gas prices can help mitigate some of the food-related impacts in Algeria, or reduce its high dependence on oils and fats from Russia.

TABLE 3 Ranking of Middle Eastern countries in the Global Food Security Index (GFSI) 2021.

Country [a, b]	Overall GFSI score (and rank)	Score (and rank) in the subcategory "affordability"	Score (and rank) in the subcategory "availability"	Score (and rank) in the subcategory "quality and safety"	Score (and rank) in the subcategory "natural resources and resilience"
Algeria	63.9 (54)	77.9 (47)	58 (56)	62 (67)	50.7 (51)
Bahrain	68.5 (43)	79.2 (46)	67.5 (21)	79.9 (41)	39.1 (107)
Egypt	60.8 (62)	66.5 (68)	60.0 (49)	60.7 (71)	52.0 (44)
Israel	78 (12)	90.6 (7)	75.2 (6)	90.07 (10)	47.6 (60)
Jordan	64.6 (49)	80.4 (42)	55.2 (64)	63.5 (64)	54.2 (36)
Kuwait	72.2 (30)	80.1 (44)	72.3 (12)	86.4 (20)	43.0 (93)
Morocco	62.5 (57)	75.1 (52)	51.8 (74)	72.3 (50)	49 (57)
Oman	70.0 (40)	88.8 (18)	57.3 (59)	83.8 (28)	45.2 (76)
Qatar	73.6 (24)	83.8 (31)	74.4 (9)	83.5 (29)	43.4 (91)
Saudi Arabia	68.1 (44)	75.0 (53)	67.8 (20)	79.8 (42)	44.3 (84)
Sudan	37.1 (110)	31.8 (107)	31.6 (109)	52.4 (85)	41.4 (99)
Tunisia	62.7 (55)	74.4 (56)	54.0 (66)	72.1 (53)	47.6 (60)
Turkey	65.1 (48)	67.6 (67)	61.6 (42)	75.8 (47)	56.4 (27)
UAE	71.0 (35)	75.9 (50)	71.3 (14)	88.8 (16)	43.6 (88)
Yemen	35.7 (112)	39.3 (96)	27.6 (112)	37.4 (108)	42.1 (96)

(a) Data for the Global Food Security Index (GFSI) 2021 available at https://impact.economist.com/sustainability/project/food-security-index/.
(b) The scores for the all GFSI indicators are between 0 and 100, while the rank indicated in () is among 113 countries (Rank 1 being the best rank).
Ranks up to 0.01 billion were rounded up (i.e., 0.045 = 0.01).

TABLE 4 Categorization of Middle Eastern countries in terms of vulnerability to food supply shocks from Russia and Ukraine.

Groups	Criteria and countries	
Group 1: Countries with a low level of vulnerability	Criterion 1: Ratio of import dependence (on Russia and Ukraine) from 10 to 20% in any category (see Table 2): *Iran, Oman, Morocco, Qatar, Saudi Arabia, United Arab Emirates*	Criterion 2: Import dependence ratio above 20% in any category but with a high GFSI above 75/100: *Israel*
Group 2: Moderately vulnerable countries	Criterion 3: Import dependence ratio of more than 20% in any category but with a moderate GFSI from 50 to 75/100: *Egypt, Jordan, Tunisia, Algeria, Turkey*	
Group 3: Highly vulnerable countries	Criterion 4: Import dependence ratio in any category of more than 20% but GFSI below 50/100: *Yemen, Sudan*	Criterion 5: Import dependence ratio in any category more than 50% but not ranked in the GFSI: *Lebanon, Libya*
Group 4: Special or unclear cases	Criterion 6: Import dependence ratio in any category from 20 to 50% but not ranked in the GFSI: *Mauritania, Palestine.*	

In Jordan, some limited level of dependence exists, mostly on Russia regarding cereals and oils, but it can be mitigated for this small-sized country (ca. 10 million inhabitants). Jordan has also mitigated past crises related to COVID-19 or the bans imposed by some countries on the exports of agri-food products. For example, in 2020, Romania banned wheat exports, thus triggering supply chain concerns across the Middle East (40). Although this ban only lasted for 6 days, it awakened some Middle Eastern countries such as Jordan, which imported one fifth of its cereals from Romania and needed to diversify its trade partners (41).

Similarly, in Turkey, dependence on cereals, the milling industry or fats and oil is strongly in favor of Russia. Particularly in cereals, Turkey–Russia trade flows are vitally important for Turkey, since Russia accounted for more 50% of the import value of cereals to Turkey in the last 5 years (Table 2). So far, Russia's agricultural exports have not been directly targeted by sanctions, but some impacts in terms of rising prices are expected (42). At the same time, despite Russia accounting for a large amount of grains imported to Turkey, Turkey is largely self-sufficient in wheat and barley, while it exports processed wheat flour to other countries in the region, such as Iraq, Syria and Yemen. Turkey is the world's largest wheat flour exporter (39). Turkish–Russian food relations remain important, and they have not suffered from the temporary bans on Russian grain exports, e.g., to ex-Soviet countries (43). As a result, Turkey is expected to mitigate the food crisis through a range of measures focusing on domestic markets; e.g., increasing domestic production, export bans, and aid to vulnerable groups, including the large population of Syrian migrants (44, 45). Besides, Turkey – with the United Nations – brokered the BSGI in mid-2022, and it has since then been one of the main destinations for Ukrainian shipments and grains (receiving more than 2 million tons out the 17.8 million tons of grains shipped from Ukraine after the BSGI as of the 18th of January 2023) (17).

4.2.2. High exposure and long-term supply reorientation: Egypt and Tunisia

Both Egypt and Tunisia exhibit high dependence on Russia and Ukraine for the import of cereals, oil seeds (in the case of Egypt) and fats and oil (see Table 2). The high value of cereal imports from Ukraine is concerning, particularly in the case of Tunisia. However, Tunisia is a much smaller country (ca. 12 million in comparison to Egypt's 102 million) with relatively stable food demands due to a smaller population growth rate; e.g., Tunisia's population grew in the last 20 years (2001–2020) by 1% on average in comparison to 2% in Egypt for the same period (calculated from data.worldbank.org). This demographic difference is also shown in Figure 1 using the key grains of wheat and corn with data on the import values from the UN Comtrade. Quantity data (using kg of imports) are less available, but they differ only slightly with regard to the percentages of imports from Russia and Ukraine. For Tunisia, despite stable imports (particularly of corn), there is a high dependence on Ukraine for the import of wheat, and even higher for corn. However, these dependence rates have significantly fluctuated over the years. In contrast, Egypt, a country of markedly rising demands and imports over the last 20 years, relies more on Russia for wheat, but percentages of imports from Ukraine for both wheat and corn have been stable or decreasing in recent years.

There are important impacts and long-term implications for Tunisia and Egypt. For Tunisia, there are compounded impacts from COVID-19, recent political turmoils, and the Ukraine war. The rising costs of food imports, fuel, and fertilizers will weigh heavily on the Tunisian economy. Since food subsidies are substantial, the higher costs could add 1.5 billion USD to the subsidy bill (46). This comes after COVID-19 caused an economic decline in Tunisia, promoting the government to ramp up social transfers and support to businesses (47). Tunisia has been undergoing a political crisis after the dismissal of the government and the freezing of parliament in July 2021; parliament was dissolved by the President in March 2022. Meanwhile, it is struggling to curb food inflation, finance its increasing subsidy bill, and certify new food suppliers before its storage capacity runs out. Tunisia has developed some grain reserve capacities with the aim of having a national storage capacity of over 6 months for wheat (48). In early 2022, the government stated that the grain reserves will last until May 2022, but there were doubts about the impact of these reserves on food availability (49). Tunisia has been a recipient of some shipments from under the BSGI (50). However, food price hikes and fuel shortages continued during 2022, while the country political crisis has worsened by the end of the same year (51).

Egypt has been exploring long-term reorientation through new sources such as India (52). While India announced the halting of its wheat exports in May 2022, Egypt had already secured some shipments prior to this announcement. Similarly, to Tunisia, Egypt will see its subsidy bill increase significantly (53). While it has some grain reserves until the end of the year, China can also help Egypt, the world's biggest wheat importer, by exporting wheat from the its huge grain stockpile (54). Egypt has also placed emphasis on support to local grain production. Table 5 compares wheat and corn production and import volumes in the Middle Eastern countries analyzed, indicating that both Egypt and Tunisia have strong domestic wheat and corn (in the case of Egypt) capacities. These domestic productions can help mitigate some long-term implications of the Ukraine war, although self-sufficiency seems difficult considering the consistently rising demands, especially in Egypt. Despite the local wheat markets suffering from the COVID-19 pandemic (55), Egypt has expanded its wheat production with the recently expanded Toskha project in the South Valley in Aswan expected to markedly increase wheat production. Egypt expects to get four millions of tons of wheat during its local harvest starting in April

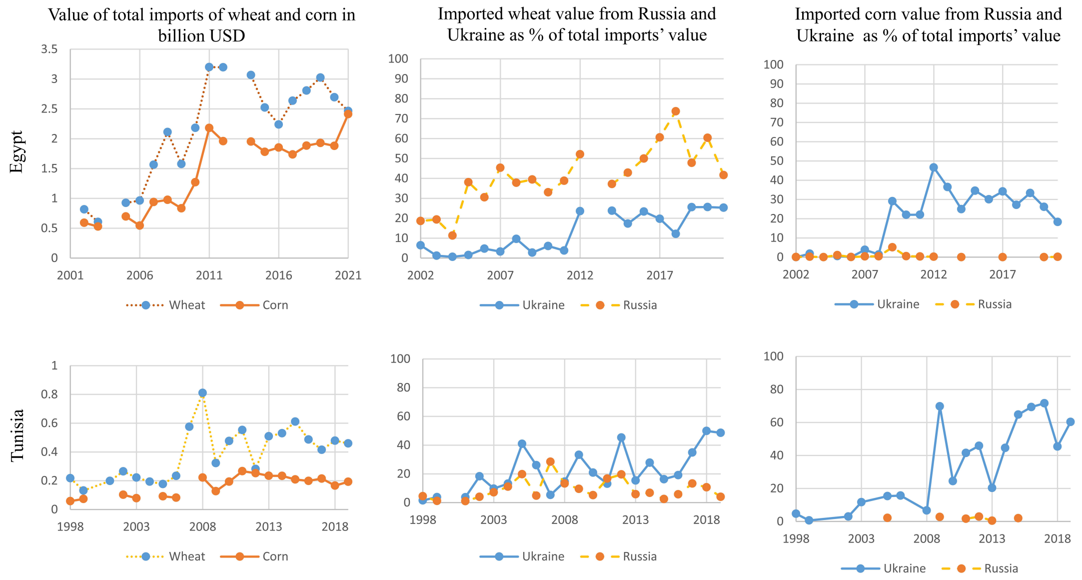

FIGURE 1
Imports to Tunisia and Egypt of wheat and corn from Russia and Ukraine [Data from UN Comtrade database for the commodity codes 1,001 "Wheat and meslin" and 1,005 "Maize" (corn)].

2023 (56). As for the rising subsidy bill, Egypt has sought the help of the IMF to alleviate short-term funding pressures, while its GCC partners (Saudi Arabia, the UAE and Qatar) have allotted a total of 23 billion USD of investment in Egypt – some of which is going to Egypt's central bank for assistance with food subsidies (57). Egypt's has been one of the main recipient countries of the BSGI (receiving ca. 683.000 tons of grains until late January 2023) (36). However, the pressure on wheat prices did not ease due to fiscal difficulties (including a currency devaluation of nearly 50% since March 2021), and a shortages of foreign currency leaving hundreds of thousands of tons of wheat stuck at ports in late 2022 (56).

4.3. Highly vulnerable countries: conflict-related context and aid interventions

4.3.1. Political fragility and food security: Lebanon, Libya, and Sudan

The three countries share a relatively high import dependence but also a fragile political-economic context. One can argue that if it were not for political instability and associated economic troubles, Lebanon, Libya and Sudan would have been much better positioned to deal with any repercussions of the Ukraine war. For example, Libya is a resource-rich (considerable oil reserves) and small-sized country, which has been suffering from the aftermath of the 2011 Arab Spring. Similar to the carbon economies of the GCC, Libya has an arid climate with no significant domestic production (see Table 5). It has relied on its ability to provide food through state-managed cereal imports, storage, and subsidies. After the Ukraine war, Libya witnessed food price hikes (58, 59). The subsidy system, through a Price Stability Fund (PSF) controlled by the government as the cereal buyer, is no longer in place since 2011, while private mills are not able to import wheat without compensation (60). There were also doubts about the government's claims regarding reserves lasting for 1 year (ibid.). The outcome of this food crisis remains open, while the only option for Libya seems to be the utilization of its oil revenues for sourcing new suppliers of cereals and reinstating a subsidy system. So far, the BSGI has proved important for mitigating some of the impacts since it provided Libya with more than 400 thousand tons of grains from Ukraine as of late January 2023 (36).

Lebanon has for a long time been one of the countries with the highest GDP per capita levels among non-carbon exporting countries in the Middle East. In recent years, Lebanon has suffered from political conflicts leading to a serious economic crisis including high inflation rates and a strong devaluation of the national currency, thus causing food insecurity (61). In the wake of the COVID-19 crisis, food insecurity increased to affect an estimated 36–39% of the adult population in 2022 (compared to 27% before the pandemic) (62). Although Lebanon has an important domestic wheat production sector, the rising cost of fuel and fertilizers in response to the Ukraine war has meant price spikes, adding to the woes of farmers already suffering from climate change and prolonged dry spells (63). With significant price increases (e.g., 25% of bread and 83% of sunflower oil in March 2021), the situation for Lebanon was dire, while the government has sought fresh imports from India, the USA, and Kazakhstan (64). The Ukraine war has not only affected food access in Lebanon, but it might have also increased unhealthy dietary patterns (65). However, importing from distant regions or decreasing import dependence through strengthening the agricultural sector in Lebanon might not decrease food costs, especially considering the economic and currency situation in Lebanon (66). At the same time, some countries such as India has already temporarily halted some exports (e.g., for wheat), except for to certain countries (e.g., Yemen). For Lebanon, aid partners such as France and Saudi Arabia have proved crucial, as they have committed to food-related projects, including for the large and vulnerable community of Syrian refugees (67). In early 2023, the European Union (EU) announced a support program of 25 million euro to help Lebanon fight food insecurity through immediate assistance and support to local agriculture (68). Besides,

TABLE 5 Wheat and corn production and imports in selected Middle East countries.

Country	Wheat production (P)[a] and imports (I)[b] in million tons						Maize (Corn) production (P)[a] and imports (I)[b] in million tons					
	2000 P	2000 I	2010 P	2010 I	2020 P	2020 I	2000 P	2000 I	2010 P	2010 I	2020 P	2020 I
Algeria	0.76	5.37	2.61	5.23	3.11	NA	0	1.48	0	2.78	0	NA
Egypt	6.56	4.9	7.18	9.93	9.00*	9.58	6.47	4.96	7.04	5.2	7.50*	8.51
Iran (Islamic Republic of)	8.09	6.58	12.14	1.41	15.00*	0.00(18)	1.12	1.18	1.66	3.63	1.40*	8.98(18)
Jordan	0.03	0.58	0.02	0.49	0.02 Im	0.76	0.02	0.41	0.03	0.51	0.02 Im	0.74
Lebanon	0.11	0.41	0.08*	0.51	0.14*	0.63	0	0.29	0.01 Im	0.35	0.00*	0.56
Libya	0.13*	NA	0.13 Im	1.06	0.13*	1.44(18)	0.01	NA	0.00*	0.31	0.00 Im	0.75
Mauritania	0.00 Im	0.09	0	0.32	0.01 Im	0.69	0.01	0	0.02	0	0.02*	0.01
Morocco	1.38	3.44	4.88	3.24	2.56	5.52	0.1	0.9	0.28	1.9	0.03	2.87
Oman	0	0.27	0	0.25	0	0.70(18)	0.02 Im	0.04	0.01 Im	0.09	0.03 Im	0.21(18)
Palestine	0.05	NA	0.02	0.07	0.03 Im	0.04	0	NA	0	1.92	0	0.03
Qatar	0	0.04	0	0.14	0	0.06	0	0.01	0	0.02	0	0.1
Saudi Arabia	1.79	0.02	1.35	1.62	0.55	0.77	0.04	1.26	0.08	1.92	0.06	3.07
Sudan	0.21	0.75(01)	0.4	1.35	0.75	5.01(18)	0.05	0.03(01)	0.04	0.04	0.01	0.00(18)
Tunisia	0.84	1.39	0.82	1.91	1.04	1.85(19)	0	0.68	0	0.89	0	1.03(19)
Turkey	21	0.96	19.67	2.55	20.5	10.00(19)	2.3	1.29	4.31	0.45	6.5	4.35(19)
United Arab Emirates	0	1.07	NA	0.85	NA	1.26(19)	0.00 Im	0.05	0.01	0.24	0.02 Im	0.56
Yemen	0.14	NA	0.27	2.65	0.10 Im	2.00(19)	0.05	NA	0.09	0.46	0.04*	0.70(19)

(a) All data of production are retrieved from the FAO stat https://www.fao.org/faostat/en/. Data annotated from FAO as follows: * = unofficial figure; Im = FAO data based on imputation methodology. All other data are official figures.
(b) All data retrieved from the UN Comtrade Database at https://comtrade.un.org/data/. NA = data not available. The following annotation applies if the year of the retrieved data differs from the indicated column year [(18) means year 2018].

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the BSGI was instrumental for Lebanon in holding and alleviating the food crisis for now (69).

Similarly, to Lebanon, international aid is a prominent short-term strategy for Sudan, which faces a serious hunger crisis, as food prices has been rising since 2021 due to domestic inflation, the dismantling of all forms of wheat subsidies in early 2022, and the fallout from the Ukraine war (70). Sudan's dire situation comes despite the country holding one of the biggest arable land potentials in Africa and some of the world's largest and oldest irrigation schemes (71, 72). While Sudan has a large agricultural output of corn, sorghum and other crops, it has been heavily reliant on Russia for its wheat production (**Tables 2**, **5**). The current crisis in Sudan is aggravated by the political turmoil following the 2019 revolution and the 2021 military coup. Since then, inflation has been very high, with bread prices increasing tenfold between October 2021 and March 2022 (73). The increase of the price of fertilizers (mainly used for wheat production in Sudan) has also decreased the domestic wheat production (74). The increased food cost comes at a time when East Africa is facing what could be the worst drought in decades (75). As of January 2023, Sudan benefited from some grain shipments under the BSGI (ca. 65 thousand tons) (36), with a promise of more to come under a food humanitarian program to countries in Africa and Asia (76).

4.3.2. Protracted conflicts and aggravated food insecurity: The tragic case of Yemen

Yemen has been one of the most publicized cases of a food insecurity emergency getting worse as a result of the Ukraine war. This is due to the compounded impacts of the current civil war since late 2014, the COVID-19 crisis and the dependence on cereal imports provided through international aid (77). The civil war has pushed people into poverty and hunger, and together with climate change impacts and the COVID-19 pandemic, Yemen is entirely reliant on food imports, with more than seven million people by the end of 2022 in the categories of "catastrophe" or "emergency" levels of hunger (78). The Ukraine war also comes at a time when aid agencies are suffering from shortfalls in funding (79). With around 80% of the 30 million Yemeni population dependent on aid, the United Nations (UN) attempted in March 2022 to raise 4.3 billion USD in aid for Yemen, but only 1.3 billion USD were promised (80). In April 2022, the United Nations reiterated the need to ramp up aid for the group of war-torn and vulnerable countries including Afghanistan, Yemen, and Syria (81).

The aggravated food insecurity in Yemen as a result of the Ukraine war is difficult to resolve in the short or medium terms. Yemen has been suffering from political fragility and recurrent political conflicts even since its independence in the mid-20th century (82). Moreover, despite having agricultural potential, decades of water over-abstraction, mismanagement, and cultivation of cash crops (including the widely used simulant *qat*) have left Yemen's agricultural sector quite weak (83). Domestic production has also been negatively affected by the destructive role of the formal private sector. This sector promotes imports in alliance with state elites, makes unsustainable demands on water supplies, and lacks the interest or the will to invest in agriculture (84). As a result of the Ukraine war, feasible short-term remedies include food aid delivered through international organizations, and/or from the reserves of neighboring GCC countries, some of which (Saudi Arabia and the UAE) are involved in the current war. While a temporary ceasefire was announced in early April 2022, some observers saw the situation deteriorating if no lasting peace materializes and donors as well as neighbors do not increase their aid (85). As of January 2023, Yemen received grain shipments under the BSGI in the amount of 150 thousand tons (36). Besides, international aid, the continuation of the ceasefire and better agricultural conditions meant an improvement of food security situation in late 2022, but high levels of food insecurity still persist for millions of Yemenis (86).

5. Discussion: Contextual determinants and action priorities

Studying food insecurities in the Middle East in the wake of the Ukraine war shows the complexity of the crisis, since it is accompanied by a set of internal and external aggravating factors. Unlike this recent crisis, previous food crises prior to the 2011 Arab Spring were related to poor harvests (e.g., in China), and thus spiking food prices; e.g., ca. 20% food inflation in Egypt in 2010–2011 (87). In the current crisis, both food supply disruptions and food price increases seem more significant, while they are accompanied by price increases in other vial commodities; e.g., fertilizers, fuel, and transport (88). Internally, this Ukraine-related crisis is hitting the Middle East very hard due to the relatively high dependence levels and the baseline political, economic, and environmental vulnerabilities. The BSGI and international aid have alleviated some of the impacts of the food security crisis in the region, but this crises is far from over as of early 2023. This paper has illustrated some of the specific contexts of the Middle East and the different levels of exposure to pressures associated with this crisis. Following from this, six contextual determinants of this exposure can be summarized:

(1) Existence of food subsidy or social security programs: Food subsidy systems or special programs providing food stamps for the most vulnerable have softened some of the impacts of the price hikes for vulnerable groups. However, in the Middle East, some countries (e.g., Algeria, Libya, Lebanon, and Sudan) have recently abandoned food subsidies, or have been unable to continue them due to political or economic difficulties. At the same time, the increased costs associated with these programs have caused fiscal difficulties, particularly in large countries such as Egypt.

(2) Cereal reserves and storage capacity: Although strategic grain reserves can be costly, some Middle Eastern countries have invested in such reserves in the aftermath of food crises in the last two decades (30, 31). Countries having significant storage capacity and available reserves were better able to avoid or delay shortfalls or price hikes despite high dependence (e.g., GCC countries and Egypt).

(3) Relative political-economic stability: Many of the most vulnerable countries in the current crisis are suffering from political conflicts and fragility (e.g., Libya, Lebanon, Sudan, and Yemen). Although this paper did not include Syria and Iraq in the analysis due to data availability, there are reports of similar food insecurities induced by the Ukraine war (23, 58). Political instability seems to be one of the factors influencing food insecurities in the aftermath of Ukraine war in other Middle Eastern countries not analyzed in this paper due to too specific a context; e.g., Palestine and Mauritania (89, 90).

(4) Baseline vulnerability to the COVID-19 pandemic: In some Middle Eastern countries such as Tunisia and Lebanon, the COVID-19 pandemic has greatly affected the states' capacity to weather the current crisis, either due to reduced state revenues or aggravated food insecurities (47, 62). In other countries, evidence exists of indirect

impacts through reduced yield (e.g., Egypt) (55), or the ramifications of regional political instability due to COVID-19; e.g., Sudan (27).

(5) Liquidity through additional revenues: In oil- and/or gas-exporting countries, the increase in carbon fuel prices after the Ukraine invasion meant additional revenues that can be used in the mitigation of the food crisis; e.g., in Algeria, Libya, or generally in the GCC countries. It is, however, not yet clear whether the additional revenues will be offset by the declining energy demand due to the global economic downturn.

(6) Existence of climatic aggravators: Recent dry spells, prolonged droughts and harvest failures can weaken the ability of local agriculture to provide food, as some narrative evidence from Sudan and Lebanon indicates (33, 63, 75).

With regard to responses in the Middle East, Table 6 summarizes the commonest interventions from this paper's comparative analysis. These responses reveal how the Middle East is using indigenous solutions such as regional cooperation with the GCC countries positioned to play a central role in alleviating some of the short-term pressures in quite vulnerable countries, particularly Egypt, Yemen, and Lebanon. It will also not be surprising to see increased regional assistance to Tunisia and Sudan if the food crisis persists. At the same time, multilateral efforts such as the BSGI have eased some of the pressure from this crisis in some highly vulnerable countries. In the long run, the Ukraine war invokes some of the lessons from the COVID-19 crisis regarding the need for special aid programs, fewer trade restrictions, and more sustainable and resilient local agriculture (27, 28, 91). At the same time, with the Middle East unlikely and undesiring (due to impacts on water) to achieve self-sufficiency, it is important to invest in strategic storage and the strengthening of the supply chain through (regional) cooperation (e.g., on trade or aid) (29, 30). At the same, a stronger collaboration between the state and the private sector, including transnational food companies and domestic private importers, has become more important for the Middle East in order to secure food commodities from the global value chain (92, 93). Encouraging sustainable consumption in order to manage food waste–e.g., Dubai's initiative for food loss reduction–is also a valuable and cost-effective food security strategy on the long-run (94).

TABLE 6 Initial response countries to food insecurity in selected Middle East countries.

Response category	Intervention types	Country examples
Trade control and diversification	Bans on cereals exports; certification of new suppliers; brokerage of deals for new shipments; buy-outs from foreign stockpiles	Algeria, Egypt Jordan, Libya, Tunisia, Turkey
Support to domestic markets	Stabilization of fertilizers costs; incentives for local farmers; increased monitoring and anti-profiteering controls	Egypt, Tunisia, Turkey, Lebanon
International cooperation and aid programs	Emergency food aid (mainly through WFP); refinancing instruments through IMF; ramping up of social programs; direct support to organizations delivering food aid	Egypt, Lebanon, Sudan, Yemen
Regional cooperation mechanisms (through GCC states)	Investments in state companies; central bank deposits; direct food-related aid	Egypt, Yemen, Lebanon

6. Conclusion

The Ukraine war has unleashed a complex global food crisis with supply interruptions and rising costs of key agricultural inputs such as fuel, transport and fertilizers. Together with the climate-related impacts and the baseline vulnerabilities related to COVID-19 and various conflicts, many countries in the global South are paying a high price for basic food commodities such as cereals and cooking oil. To better understand the reach of such compounded food crises, the Middle East serves as an illustrative case related to a high dependence on food imports from Russia and Ukraine and a very difficult political-economic context. Even prior to COVID-19 and the current Ukraine-related crisis, Middle Eastern countries have suffered from repeated food shocks that have caused or exacerbated political crises and state collapse, and many of these countries were hard-hit by the food-related spillovers of the COVID-19 crisis. However, despite the importance of food imports from Russia and Ukraine for the region, not all Middle Eastern countries will be highly exposed to the food crisis in the wake of the Ukraine war.

Moderately vulnerable countries such as Algeria, Jordan and Turkey face "manageable" pressures due to lower levels of dependence, availability of alternative production domestically, or well-functioning food sectors. They also demonstrate the importance of food diplomacy in these countries in order to maintain the flow of vital cereals, e.g., Algeria with France, Turkey with Russia, or Jordan with Romania. Within the same group of moderately vulnerable countries, Egypt and Tunisia stand out as facing more exposure due to high dependence rates. However, Egypt and Tunisia have ramped up their food storage capacities in the past years and invested in expanding wheat infrastructure. Tunisia has had rather stable but fluctuating imports from Ukraine. In both cases, the exposure to the Ukraine-related food crisis is complicated by growing populations (Egypt), COVID-19 turbulence, and an increase in internal political conflicts (Tunisia). Some immediate exit strategies relied on securing additional funds (e.g., from Gulf states) for satisfying the soaring costs of food subsidies while re-orienting the food import strategies toward new sources in Asia. Later, the release of some shipments from Ukraine helped lower the supply pressure although economic difficulties and high food prices persisted.

The case of the group of highly vulnerable countries (Lebanon, Libya, Sudan and Yemen) will prove quite concerning. While one would expect countries such as Libya to funnel some of their (increased) oil revenues toward mitigating the new crisis, Lebanon, Sudan and Yemen will be relying on international cooperation in the short and medium term, including shipments under the BSGI. These countries illustrate how political-economic instability is aggravating the food crisis in the Middle East in the wake of the Ukraine war. Political-economic stability is one of six vulnerability determinants identified by this paper, which can be examined in the future through case studies that are more detailed. However, state responses can still play an important role in deciding the outcomes of the current crisis. Alongside classic responses such as trade controls, supply diversification, public support, and aid, this paper has argued that the relatively comfortable position of Arab Gulf countries will play a crucial role in mitigating some of the impacts on the Middle East through regional cooperation and aid-related food security and fiscal stability. With regard to future food security strategies, the Ukraine war has highlighted the importance of both domestic, regional and international resilience and adaptation measures. Enhancing local capacities in the areas of storage or the procurement of food supplies (e.g., through stronger public-private collaborations) will be important for mitigating future shocks. As previous crises have also shown (e.g., COVID-19), local agriculture remains an important food security tool in some Middle Eastern countries, but it should be securitized using sustainability and efficiency criteria (particularly the issues of water availability and use efficiency). While special aid programs from the international community toward the most vulnerable and conflict-ridden communities in the Middle East is essential for overcoming the current food crises, strengthening regional frameworks for collaboration on food security has emerged as an interesting long-term pathway for the Middle East region.

Data availability statement

Publicly available datasets were analyzed in this study. This data can be found here: UN Comtrade Database https://comtrade.un.org.

Author contributions

The author confirms being the sole contributor of this work and has approved it for publication.

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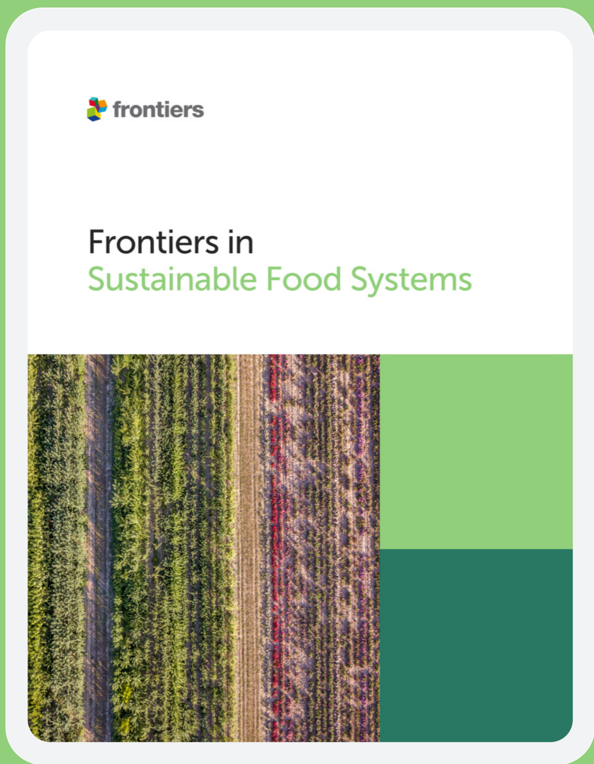

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