Research Topics

# Climate science, solutions and services for net zero, climate-resilient food systems


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# Climate science, solutions and services for net zero, climate-resilient food systems

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# Editorial: Climate science, solutions and services for net zero, climate-resilient food systems

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KEYWORDS

**food systems, climate resilience, climate change, net zero, solutions, climate services, weather and climate, climate impacts**

Editorial on the Research Topic
Climate science, solutions and services for net zero, climate-resilient food systems

Food systems are both a major contributor to global greenhouse gas emissions (Costa et al., 2022) and strongly impacted by climate and weather (Falloon et al., 2022). Solutions to deliver net zero food systems therefore need to take climate impacts, adaptation, and resilience into account to ensure they are appropriate in a changing climate and do not conflict with adaptation goals. Food system adaptation options must also consider potential trade-offs, consequences, and synergies with net zero and other objectives such as the Sustainable Development Goals. Solutions for net zero, climate resilient food systems therefore require systematic, interdisciplinary approaches across academia, governments, business, NGOs, and the public. This Research Topic showcases a Research Topic of studies covering cutting edge science and thought leadership towards the goal of net zero, climate-resilient food systems.

Several papers use case study events or assess current and future practical climate adaptation and net zero practices in farming and food systems businesses. An exploration of farmers' perception of climate adaptation strategies in the rice-growing zone of Punjab, Pakistan by Khan et al. revealed significant perceived climate changes, while the extent of adaptation was strongly linked to education and access to climate information and credit services. The principal factors determining adaptation decisions included farmers' age, primary occupation, income, landholding, access to irrigation, credit, climate information, and agricultural extension services; hence improving the alterable factors amongst these should improve resilience of the rice farming system.

Sarker et al. assess the benefits of conservation tillage and residue management to soil health and crop productivity in a Bangladeshi rice-maize cropping system. Compared to conventional tillage, the overall improvement in soil conditions gradually increased crop productivity, and improved farm profitability compared

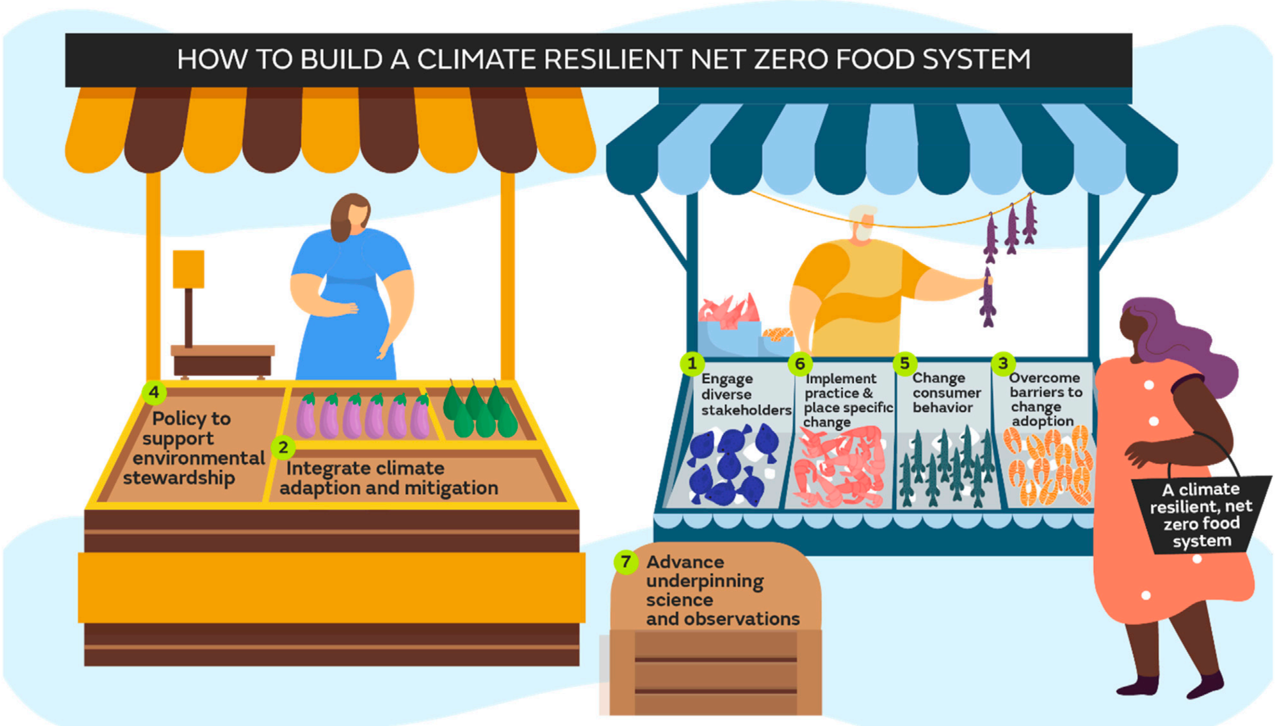


FIGURE 1
Key elements for a climate-resilient, net zero food system. (c) Crown Copyright, Met Office.

to conventionally tilled rice and maize crops. Conservation agriculture could therefore be an appropriate practice for sustaining soil fertility and crop yield under rice-maize systems in light-textured soils in Bangladesh.

Kumar Jha et al. report results from experimental studies in the rice-wheat system of Bihar, India that evaluate the feasibility of early rice transplanting combined with a community irrigation approach. These practices increased rice yield and water productivity, compared to late-sown crops, while timely wheat harvesting allowed cultivation of an additional summer crop. Overall, this approach to managing climatic risks and variability increased the productivity of the rice–wheat cropping system.

Sakrabani analyses the opportunities and challenges for organo-mineral fertilisers (OMFs) in enabling food security and meeting net zero goals, identifying policy interventions that balance environmental protection and meeting food security. Short-term priorities include development of guidelines, energy incentives for drying feedstocks and renewable energy; in the medium-term, evidence gathering from long-term field trials, funding to support innovation, and regional policy harmonisation; and in the long-term feedstock certification and joined-up waste-fertilizer policy.

Davie et al. use the record-breaking United Kingdom heatwave of 2022 as a case study to explore the impacts on the poultry and wheat sectors, and to identify potential adaptation options for a climate-resilient, net-zero food system. Both negative and positive heatwave impacts were felt across the food system, from greater energy costs for cold storage, retail refrigeration failure, and livestock heat stress but also increased wheat yields. A range of adaptation measures are proposed for both poultry and wheat.

Asif et al. present a novel methodology for developing a sustainable business model (SBM) in the food, beverage, and tobacco sector, using data from 252 businesses that reported to the Carbon Disclosure Project (CDP). Their analysis identified, prioritized and mapped a range of environmental sustainability themes and 150 green practices that could contribute to emission reduction targets, resulting in a net-zero value proposition to customers.

The remaining papers tackle key challenges at the broader policy level. Gelardi et al. review the evidence for agricultural soils to contribute to net zero goals, examine existing support strategies and emerging markets, and recommend ways to synthesize approaches into a cohesive policy portfolio for the US to deliver effective and equitable outcomes.

Moghayer et al. apply a multi-level participatory scenario approach combined with modelling and decision support tools to develop scenarios in support of future food security policy in Bangladesh. Their future scenarios show that diverse pathways are possible, but with very different food security and low-carbon development outcomes.

Andrews et al. draw on agroecological principles to propose a framework for aligning food-systems policy to provide multiple benefits. Their six-part framework can underpin public health, environmental sustainability, economic stability, social cohesion, and national security and sovereignty. The seven tactical implementation principles they propose can help integrate community-scale efforts to establish food systems and ensure food systems policy effectiveness.

To advance solutions and services that support the goal of climate-resilient, net-zero food systems and better food security outcomes, several key themes emerge from the papers presented here, noting that the challenges highlighted below should not dissuade action Gelardi et al.:

1. Broad and diverse stakeholder engagement across the agri-food supply-chain and beyond in solution co-design and development (Asif et al.; Gelardi et al.), including youth and poor rural communities (Moghayer et al.).
2. Effective integration and joint prioritization of climate adaptation and mitigation options, alongside consideration of their trade-offs, consequences, co-benefits and interactions. This should include social, economic and environmental dimensions and pressures for land (Davie et al.; Gelardi et al.; Kumar Jha et al.), and balancing short and long-term priorities (Moghayer et al.).
3. Addressing barriers to adoption and structural issues (Davie et al.; Gelardi et al.; Khan et al.) in climate adaptation and net-zero.
4. Integrated policy that supports effective environmental stewardship and is underpinned by well-functioning governance systems and political will (Andrews et al.; Moghayer et al.; Sakrabani).
5. Enabling shifts in consumer behaviour (Moghayer et al.).
6. Implementation of practice- and place-specific programs of change (Gelardi et al.).
7. Advancing underpinning science, modelling, tools, methods, frameworks and observational data to be fit for purpose in decision-making and policy support (Gelardi et al.; Sarker et al.).

## Author contributions

PF: Conceptualization, Investigation, Writing–original draft, Writing–review and editing. AJ: Writing–original draft, Writing–review and editing. SB: Writing–original draft, Writing–review and editing. SK: Writing–original draft, Writing–review and editing. MR: Writing–original draft, Writing–review and 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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# Conservation tillage and residue management improve soil health and crop productivity—Evidence from a rice-maize cropping system in Bangladesh

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The rice-maize (R-M) system is rapidly expanding in Bangladesh due to its greater suitability for diverse soil types and environments. The present conventional method of cultivating puddled transplanted rice and maize is input-intensive, decreases soil health through intense ploughing, and ultimately reduces farm profitability. There is a need to investigate alternatives. Accordingly, we conducted a replicated 2-year (2020–2021) field study to investigate the effects of conservation agriculture (CA) based tillage and crop establishment (TCE) techniques and residue management practices on the physical, chemical, and biological properties of soil along with crop productivity and the profitability of rice-maize systems in the sandy loam soil of Northwest Bangladesh. Two TCE techniques Puddled transplanted rice (PTR) followed by Conventional tillage maize (CTM) and strip tillage direct-seeded rice (STDSR) followed by strip-tilled maize (STM) were assigned to the main plots and different percentages of crop residue retention (0, 25, and 50% by height) were allocated to the subplots. Results showed that a reduction in bulk density (BD), soil penetration resistance (SPR), and increased soil porosity were associated with STDSR/STM-based scenarios (strip tillage coupled with 25 and 50% residue retention). The soil organic carbon (SOC) fractions, such as dissolved organic C (DOC), light and heavy particulate organic matter C (POM-C), MAOM, and microbial biomass C (MBC) levels in the 0–10 cm layer under ST based treatments were 95, 8, 6, 2 and 45% greater, respectively, compared to CT with no residue treatment. When compared to the CT treatment, the DOC, light POM-C, heavy POM-C, and MAOM in the 10–20 cm layer with ST treatment were 8, 34, 25, 4 and 37% higher, respectively. Residue retention in ST increased average rice, maize, and system yields by 9.2, 14.0, and 14.12%, respectively, when compared to CT. The system gross margin and benefit-cost ratio (BCR) were \$1,515 ha$^{-1}$ and 1.90 under conventional tillage to \$1,696 ha$^{-1}$ and 2.15 under strip-tillage practices. Thus, our study suggests that CA could be an appropriate practice for sustaining soil fertility and crop yield under R-M systems in light-textured soils or other similar soils in Bangladesh.

KEYWORDS

**direct seeded rice, strip tillage, residue management, conservation agriculture, system productivity, carbon fractions**

## 1 Introduction

The main rice-based cropping system in Bangladesh, termed rice-rice (R-R) is practiced through a monsoon (*T. aman*) crop in the rainy *Kharif* season, followed by a winter (*Boro*) crop during the winter season when irrigation water is available. The area covers about 2306 M ha of land in 2014, 2015 (Nasim et al., 2017). When water is scarce, maize, wheat, potato, vegetables, or other crops are grown instead of *Boro* to increase profits. Among the cropping systems practiced, rice-wheat (R-W) system are predominant in tropical to subtropical climate areas of the Indo-Gangetic plains (IGP) of Bangladesh, Nepal, India and Pakistan because they serve a significant role in achieving food security and income for rural and urban populations (Chaki A. K. et al., 2021). During the 2000s, the maize area increased considerably, changing from 50 M ha in 2000 to 401 M ha in 2017, 2018 (DAE, 2019). This change is mainly because of the rising demand for maize grain for poultry and fisheries and also for the human diet (Ali et al., 2008; Timsina et al., 2010). This rice-maize (R-M) system occupies approximately 1.31 M ha in Bangladesh, India, and Nepal, explaining their importance in the region (Gathala et al., 2015).

In the north-western part of Bangladesh, farmers experience a delay in maize planting when excessive soil moisture has caused a delay in harvesting the previous rice crop. This happens frequently and any kind of tillage operation is inadvisable until the soil moisture has reduced sufficiently to allow traffic without compaction or slippage. Usually, farmers use conventional tillage, which involves up to 3–5 passes of slow-speed rotary tillage with a two-wheeled, tractor (2WT) driven power tiller. This is the reason why farmers need an additional 2,3 weeks after the rice harvest to carry out tillage operations before planting maize, which significantly delays planting. (Gathala et al., 2015). Therefore, the maize crop is affected by heat stress during the reproductive stage if sown late (Timsina et al., 2010), which may cause a 12–22% yield loss (Ali, 2006). The literature suggests that to minimize the yield gap and achieve the potential yield, maize crops should be planted as soon as possible after the rice harvest (Timsina et al., 2010).

In Bangladesh, a significant amount of soil organic carbon (SOC) has been lost over the last decade (BBS, 2017; Uddin et al., 2019. This is due to a decrease in inherent soil fertility, and poor soil and irrigation management, along with the adoption of inappropriate intensive farming practices such as intensive tillage by a two-wheel tractor driven power tiller for land preparation (Krupnik et al., 2013), use cow dung as a fuel, residue removal and burning practices, which accelerate the physical disruption of soil aggregate and decrease soil organic carbon (SOC) (Gupta Choudhury et al., 2014; Lenka et al., 2015), and microbial activities (Curaqueo et al., 2011).

In the context of delayed planting, heat stress and soil health deterioration, the application of climate-smart agriculture (CSA), for example, conservation agriculture (CA) techniques, which involve minimum disturbance of soil, residue retention/cover crops (Blair et al., 2006), and crop rotation (Parihar et al., 2016), may be especially relevant. With no-till practices or minimum tillage in CA systems, there is little need to prepare the land for planting (FAO, 2001). This could allow early sowing, avoid heat stress, and keep soil moisture (Kucharik, 2006; Marongwe et al., 2012). According to previous research, no-till with crop residue retention has a significant impact on soil erosion control, enhanced soil structure by maintaining soil aggregates (Galdos et al., 2009), minimum oxidation of soil organic matter, reduced runoff and increasing crop productivity (Roose and Barthes, 2001; Erenstein, 2002; Chaki A. K. et al., 2021). The agronomic productivity is increased when 25–50% (1.3–2.5 Mg ha$^{-1}$) of the entire crop residues are incorporated with a chisel plough (Bahrani et al., 2007). Another finding from Kumawat et al. (2022) who conducted a field experiment with varying amounts of residue retention under CA based maize-chickpea cropping system. They found that the lowest bulk density, higher soil moisture content and soil available nitrogen, phosphorus and organic carbon was recorded in 60 and 90% of crop residue plots compared to no residue retained plots. Vasconcelos et al. (2018) suggested that 6 Mg ha$^{-1}$ of crop residue would be a good way to prevent soil C loss and keep the soil covered. Furthermore, several studies have suggested that retaining a moderate quantity (50%) of crop residues can increase crop productivity. Under irrigated conditions, a short-term evaluation of applying crop residue at different rates (ranging from 25 to 100%) and with varied tillage techniques showed that applying residues at R100, followed by R75 and R50, significantly enhanced soil organic carbon and wheat grain production (Mirzaei et al., 2021. The benefits of reduced tillage practices can be more productive if optimally combined with crop residue management and mixed-cropping systems (crop rotation diversification). In this context, future research is needed to investigate the effect of crop residue management and different cropping systems on changes in soil parameters, and crop productivity (Asargew et al., 2022).

Crop residue returning, both aboveground or belowground biomass, to the field after harvesting a crop is a globally accepted good practice for improving soil health parameters. To maintain soil quality and ensure sustainability, residue returning must be implemented scientifically. This is because tillage practises, how residue is returned to the soil, and how long it takes, and weather conditions, can have an effect on achieving the maximum benefit from residue retention (Naresh et al., 2021). Examples include Chalise et al. (2019) who reported that mulch retention had a positive impact on soybean yield. Another study was conducted by Krupnik et al. (2014) at two locations in Bangladesh and found inconsistent results; at one location, there was no difference in the tillage system in either year, whereas, in another location, conventional tillage gave a higher yield in the first year but strip-tillage gave higher yields in the second year. So future research is needed to understand the performance of various tillage techniques, such as conventional tillage and no tillage under equal residue retention, in a range of crop, soil, and climatic conditions (Singh et al., 2020). Clearly, given the lack of understanding of these issues, investigation of appropriate tillage with crop establishment methods and straw return in R-M systems is therefore critical for rice and maize production, ensuring food security, and fulfilling the feed demand from livestock, poultry and fish industries in Bangladesh.

Many studies have been conducted separately on rice and maize production systems such as R-R, and R-W systems in Asia, and tillage and nutrient management (Timsina and Connor, 2001), although studies on the R-M systems in South Asia, especially in Bangladesh are still limited (Timsina et al., 2018). To cover this information gap, it is important to investigate the long-term sustainability of R-M system production in Bangladesh using various tillage alternatives. It is hypothesized that Conservation Agriculture (CA) techniques which considered zero, strip, and reduced tillage, crop residue retention, and diversified maize-based crop rotations, improve soil health parameters such as physical, chemical and biological, compared to conventional tillage and the existing dominant R-R, R-W cropping system of the region. Hence, in response to this knowledge gap and to test the hypothesis, the objectives of the present study were to investigate the short-term effects of different tillage practices with residue return on the physical and chemical properties, and biological activity under a rice-maize rotation in sandy loam soil in Bangladesh.

# 2 Materials and methods

## 2.1 Site and soil characteristics

The field experiment was conducted at the Agricultural Research Station (ARS), Bangladesh Agricultural Research Institute, Rajbari, Dinajpur during the 2019–20 and 2020–21 seasons of Aman rice (rainy season) and maize in the North-Western part of Bangladesh (Figure 1). The experimental site is located in the Old Himalayan piedmont plain (AEZ 1) (BARC, 2015; FAO/UNDP 1988). The soil of the experimental site is a well-drained sandy loam with pH 6.7, and the initial physical, chemical and biological properties of the soil are given in Table 1.

## 2.2 Climatic characteristics

Figure 2 highlights that during the experimental period the monthly maximum temperatures varied from 22 to 34°C and the minimum temperature from 10 to 27°C at the study site. The average 2 years (2019–21) annual rainfall was 1796 mm and overall, 80% of this fell during the May to October period.

### 2.2.1 Rice season

The total rainfall during the rice season (June-November) was 1950 mm in 2019 whereas 2,486 mm in 2020. Total monthly rainfall during June was 297 in 2019 whereas it was 403 mm in 2020 and the total rainfall in July ranged from 618 mm in 2019 to about 680 mm in 2020. June and July rainfall are very important for sowing direct-seeded rice (DSR), whereas rainfall during July is crucial for transplanted rice. The average maximum temperatures from June to November were 29–34°C while the minimum temperatures were 16–27°C.

### 2.2.2 Maize season

The weather pattern fluctuated across the 2 years. The total amount of rainfall in the winter maize growing season (November-May) was higher in 2020–2021 (743.7 mm) than in 2019–2020 (601.3 mm). Maize is grown during the cool (11–22°C) winter period (Mid-November to the first week of May) and at that time rainfall is very limited. The monthly mean daily maximum temperatures from November to May were 223–340°C while the minimum temperatures were 11.10–20.14°C, respectively.

## 2.3 Experimental details

The experiment was laid out in a 2-factor split-plot design with three replications. Main plot treatments were puddled transplanted rice (PTR) followed by conventional tillage maize (CTM) and strip tillage direct-seeded rice (STDSR) followed by strip-tilled maize (STM) and the sub-plot treatments were three rice residue management options (0, 25 and 50%) either retained on the soil surface in strip tillage plots or incorporated into the soil in conventional tillage plots. The maize stalks were cut and chopped into 5–10 cm lengths and spread uniformly over the whole plot across the treatments. The treatments in the current study have been discussed details in Table 2.

## 2.4 Crop management

Twenty-two-day old seedlings were manually transplanted with a spacing of 20 cm × 15 cm and 2,3 seedlings per hill. All DSR plots were sown with zero-till maize/multi-crop planter

TABLE 1 The initial status of soil properties at the experimental site.

**A. Soil physical properties**

| Depth (cm) | Bulk density (Mgm-3) | Particle density (Mgm-3) | Moisture content (%) | Field capacity % (0.3 bar) | Soil penetration resistance (SPR) (kPa) | Soil particle (%) | | | Soil texture |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Sand | Silt | Clay | |
| 0–10 | 1.42 | 2.51 | 20.70 | 27.4 | 870 | 60 | 22 | 18 | Sandy loam |
| 10–20 | 1.47 | 2.42 | 19.67 | 23.1 | 1,080 | 72 | 16 | 12 | Sandy loam |
| 20–30 | 1.59 | 2.47 | 16.11 | 22.4 | 1,380 | 70 | 16 | 14 | Sandy loam |
| 30–40 | 1.64 | 2.56 | 20.37 | 24.5 | 1,680 | 66 | 20 | 14 | Sandy loam |
| 40–50 | 1.60 | 2.49 | 21.27 | 29.9 | 1,170 | 62 | 24 | 14 | Sandy loam |
| 50–60 | 1.53 | 2.58 | 30.87 | 29.2 | 480 | 64 | 18 | 18 | Sandy loam |
| 60–70 | 1.54 | 2.48 | 26.50 | 36.7 | 440 | 72 | 17 | 11 | Loamy sand |

**B. Soil chemical and biological properties**

| Depth (cm) | pH | OM (%) | Total N (%) | Available | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | P (mg kg-1) | K (meq/100 g) | S (mg kg-1) | Zn (mg kg-1) | Mn (mg kg-1) | Fe (mg kg-1) | B (mgkg-1) |
| 0–10 | 6.15 | 0.96 | 0.08 | 18 | 0.16 | 20.7 | 0.89 | 10.1 | 53.2 | 0.41 |
| 10–20 | 6.20 | 0.83 | 0.05 | 17 | 0.18 | 20.8 | 0.86 | 9.5 | 47.8 | 0.38 |
| 20–30 | 6.25 | 0.75 | 0.04 | 12 | 0.11 | 19.6 | 0.74 | 9.6 | 45.2 | 0.32 |
| 30–40 | 6.35 | 0.65 | 0.04 | 10 | 0.10 | 20.9 | 0.72 | 5.2 | 29.1 | 0.32 |
| 40–50 | 6.38 | 0.54 | 0.03 | 10 | 0.09 | 21.04 | 0.54 | 5.1 | 26.9 | 0.24 |
| 50–60 | 6.45 | 0.48 | 0.02 | 9 | 0.07 | 24.1 | 0.52 | 2.4 | 20.6 | 0.23 |



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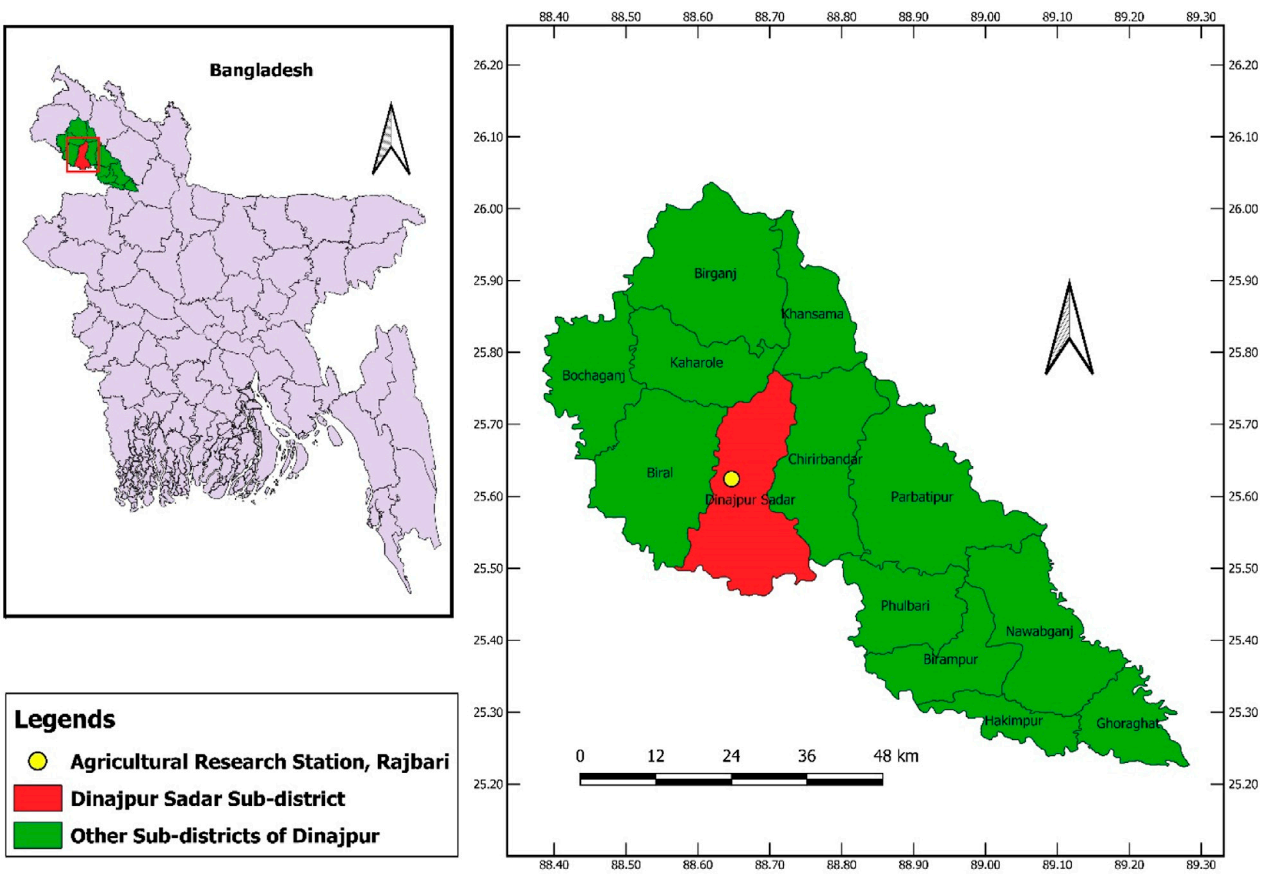


FIGURE 1
The whole green highlighted areas represent the experimental district and the red areas represent the Dinajpur Sadar Sub-district on the map of Bangladesh. The yellow point is the location of the experimental site.

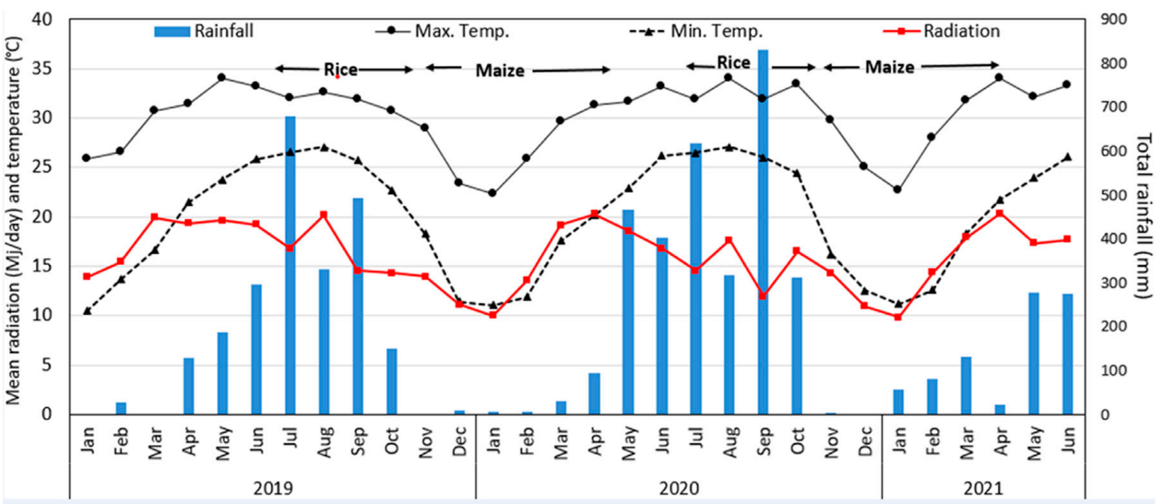


FIGURE 2
Observed rainfall, solar radiation, and maximum and minimum temperatures in the study area.

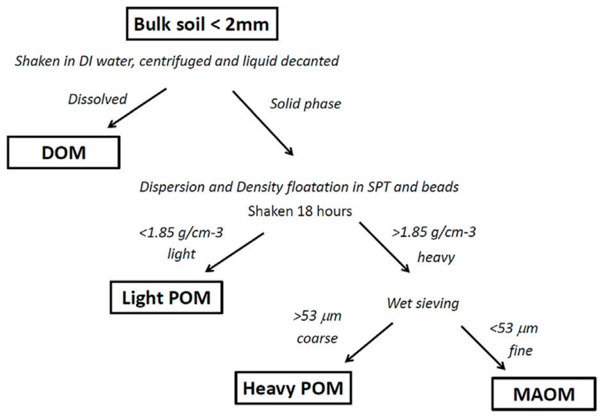


FIGURE 3
Schematic diagram showing SOC fractionation DOM = Dissolved Organic Matter, Light POM = Particulate Organic Matter, density, Heavy POM = Heavy Particulate Organic Matter, and MAOM = Mineral-Associated Organic Matter. (Modified from Robertson et al., 2019).

having an inclined plate seed metering system (model, BMWRI-ZT) with 20 cm row using a 30 kg seeds ha$^{-1}$. The sowing of DSR and wet bed rice nursery for PTR was done at the same time in the third week of July each year. In CTM plots, maize (BARI Hybrid maize-9) dibbled manually at 20 kg ha$^{-1}$ maintaining 60 cm × 20 cm plant spacing in the third week of November whereas STM plots were sown by the zero-till maize/multi-crop planter (model, BMWRI-ZT). In the experiment field, rice was fertilized with 54 kg N + 12 kg P + 60 kg K + 9 kg S + 1.2 kg Zn ha$^{-1}$, while maize received 218 kg N + 76 kg P + 80 kg K + 37 kg S + 11 kg Mg+ 2.1 kg Zn ha$^{-1}$. No pre-planting herbicides were used in the CT plots, but pyrazosulfuron, a broad-spectrum post-emergence herbicide, was used in the STDSR plots and glyphosate was used in the CTM plots to control weeds.

## 2.5 Harvesting and yield measurements

Both crops, rice and maize, were harvested at the physiological maturity stage. The rice crop was harvested in DSR plots during the first week of November, whereas PTR plots were harvested in the second week of November in both years. Rice was harvested manually in an area of 3.7 m$^2$ within a field of each plot, following a zig-zag pattern to avoid border effects. For the maize crop, a net plot area of 35 m$^2$ was harvested and the biomass was dried in the field for 3–5 days under the Sun. The rice grain yields were adjusted to a 12% moisture content whereas for the maize grain it was 14%. The dry weight of stubble/straw was recorded after drying at 70°C to a constant weight.

Annual system productivity was determined as rice equivalent yield (REY) by converting the yield of maize crops into rice equivalent yield

$$REY = \frac{\text{Yield of maize crop }(\text{kg ha}^{-1}) \times \text{Price of non} - \text{rice crop }(\text{US\$/kg})}{\text{Price of rice }(\text{US\$/kg})} \quad (1)$$

The prices of rice and maize used for the calculation were US$ 0.21, and US$ 0.24 kg$^{-1}$, respectively. The grain prices of all the component crops were determined based on local market prices in BDT and later converted to US$ (1 US$ = 85.00 BDT, the average exchange rate in the experimental period.

## 2.6 Leaf chlorophyll

For the rice crop, the chlorophyll content was determined by using a chlorophyll meter (SPAD-502, Minolta Camera Co. Ltd., Osaka, Japan) during the vegetative and reproductive phases, a mature leaf being taken from the top of the plant to measure the SPAD values.

## 2.7 Soil sampling and processing

The soil was collected from the experimental fields before establishing the treatments in 2019, and in 2021 after the harvest

TABLE 2 Description of experimental treatments.

| Treatments | Treatments details | Descriptions of ST and CT |
|---|---|---|
| $T_1$ (PTR/CTM +0% residue) | Puddled Transplanted Rice—Conventional till Maize | Strip tillage (ST): Multi-crop planter (model, BMWRI-ZT Manufactured by BMWRI, Dinajpur) in a single operation were used for DSR and STM. Tilled and seed placement between 5 and 7 cm |
| $T_2$ (PTR/CTM +25% residue) | Puddled Transplanted Rice—Conventional till Maize | |
| $T_3$ (PTR/CTM +50% residue) | Puddled Transplanted Rice—Conventional till Maize | |
| $T_4$ (DSR/STM +0% residue) | Direct Seeded Rice—Strip till Maize | Conventional tillage (CT): Three-four times full rotary tillage by 2 W tractor operated by power tiller were used for PTR and CTM. The depths of tillage are about 6–9 cm. Incorporation of crop residue with one-time land leveling. Puddling (wet tillage) was done twice in 8–10 cm of standingmi power tiller |
| $T_5$ (DSR/STM +25% residue) | Direct Seeded Rice—Strip till Maize | |
| $T_6$ (DSR/STM +50% residue) | Direct Seeded Rice—Strip till Maize | |

of the maize crop in the second year. Briefly, nine representative soil samples were randomly taken from the experimental field at 0–10 and 10–20 cm depths and subsequently composited based on depth for the analysis of soil chemical properties. In addition, another soil sample was collected (from 0 to 10, 10–20, 20–30, 30–40, 40–50, 50–60 and 60–70 cm soil profile) by digging a 100 cm deep soil pit in the experimental site to determine the initial physical and chemical properties of the soil layers. After 2 years of the rice-maize cropping systems, in May 2021 (after the maize harvest), three representative soil samples were collected from each plot at 0–10 and 10–20 cm depths and composited according to depth for the analysis of carbon fraction in each depth. For microbial biomass carbon, soil samples were collected from each plot at 0–5 and 5–10 cm depths. The soil samples were gently sieved through a 4 mm mesh sieve to remove large organic substances. After sieving, the soil samples were passed through a 2 mm sieve and stored in plastic zipper bags at 4°C before microbial biomass carbon analysis. Soil penetration resistance (SPR) was calculated at 0–10 and 10–20 cm depths before starting the experiments and after the end of the experiment in the second year using a Hand Penetrometer (Eijkelkamp Equipment, Model 06.01, and Serial No. 11911698/11, Giesbeek, Netherlands).

## 2.8 Analytical methods

### 2.8.1 Soil physical and chemical properties

Organic matter (OM), nitrogen (N), phosphorus (P), potassium (K) and zinc (Zn) were measured following standard procedures (Page et al., 1989). Soil pH was measured with a glass electrode pH meter (WTW pH 522) at a soil-water ratio of 1:2.5 as described by (Page et al., 1982), soil organic C was determined by Walkley and Black's wet oxidation method as described by Jackson. (1973) and total N was determined by micro-Kjeldahl method (Page et al., 1989); available P was measured following the Olsen method (Jackson, 1973), exchangeable K was quantified following the NH4OAc extraction method (Black, 1965), S was determined by the turbidimetric method through a spectrophotometer using a wavelength of 420 nm (Page et al., 1989). Ca was measured by the complexometric method of titration using Na2-EDTA (Disodium ethylenediaminetetraacetic acid) as a complexing agent (Page et al., 1989), Mg was estimated by using the NH4OAc extraction method (Black, 1965), and available Zn, Cu, Fe, and Mn were measured by using the diethylenetriamine Penta acetic acid (DTPA) extraction method (Lindsay, 1978). Particle size distribution was assessed by the hydrometer method (Bouyoucos, 1962), and the soil textural class was calculated using the USDA textural triangle. Bulk density and particle density of the soil samples were determined by the core sampler method and Pycnometer method, respectively (Karim et al., 1988). The soil porosity was calculated from the relationship between bulk density and particle density

$$\text{Porosity}\,(\%) = \left(1 - \frac{\text{BD}}{\text{PD}}\right) \times 100 \tag{2}$$

where, BD is bulk density (Mg $m^{-3}$), PD is particle density (Mg $m^{-3}$).

### 2.8.2 Carbon fractionation by size and density

We determined the TOC contents of composite soil samples by the size-density fractionation technique proposed by Robertson et al. (2019). The main goal was to figure out how SOM changes in each of the different soil fractionations. With this approach, four soil fractions were made: DOM (dissolved organic matter), Light POM (particulate organic matter, density, < 1.85 Mg $m^{-3}$), Heavy POM (heavy particulate organic matter, size >53 μm), and MAOM (mineral-associated organic matter, < 53 μm) (Figure 3). To assess DOM, 10 g of air-dried soil was passed through a 2 mm sieve and placed in a 50 ml centrifuge tube, then 30 ml of deionized water was added and the sample was shaken for 15 min at 95 rpm. After that, the sample was centrifuged for 15 min at 1874 g (calculate rpm for 19.2 cm SoG rotor = 2,876 rpm), and the soil solution was filtered using 20 μm Whatman No 1 filter paper. After that, the sample was analyzed within 48 h by elemental analyser (Vario micro cube CHNOS Elemental Analyzer; EuroEA3000).

The light POM technique begins with the first step, following that, the solid material was retained on the filter in the pre-weighed aluminium pan in order to measure the weight of the light fraction. Besides this, 20 ml of sodium polytungstate (SPT) 1.85 Mg $m^{-3}$was added to a centrifuge tube containing the centrifuged 10 *g* soil, and shaken for 18 h on a reciprocal shaker at 95 rpm to disperse the sample and then centrifuged for 30 min at 1874 g. It was then collected in the previously weighed aluminium pan and dried at 60°C in the oven. The light POM was then recorded.

For the heavy POM, the procedure was firstly to remove the SPT by repeatedly rinsing the soil with deionized water: deionized water was added (to the 40 ml mark), the sample was shaken to mix it, it was centrifuged, and the water discarded and finally passed onto a 53 μm sieve. To assess MAOM, we collected the sample that has passed through the sieve into a pre-weighed aluminium pan–this was the silt and clay-sized organic matter fraction (MAOM). Finally, we put 10 mg of each of the ground solid fractions (Light POM, Heavy POM, and MAOM) into 9 × 5 mm silver capsules, added 30 μl of 15% hydrochloric acid, and oven-dried them at 60°C, and the samples were analyzed in the elemental analyser (Vario micro cube CHNOS Elemental Analyzer; EuroEA3000). The soil organic carbon (SOC) stock was calculated according to the following equation (Batjes, 1996):

SOC stock (Mg $ha^{-1}$) = SOC concentrations (%) × bulk density (Mg $m^{-3)}$ × depth (cm).

The carbon stock computed in different fractions considering amount of visible piece of degraded plant material in every fraction as well as % of SOC concentrations.

### 2.8.3 Microbial biomass carbon (MBC)

The chloroform fumigation extraction method was adopted to estimate the amount of microbial biomass C in soils. Fumigated and non-fumigated soils were extracted with 0.5 M $K_2SO_4$ (soil: $K_2$SO4 solution = 1:4) and shaken for 30 min and then, filtered. From the extract, the amount of biomass C was determined according to the method described by Vance et al. (1987).

## 2.9 Economic analysis

Partial economic analysis under a range of tillage practices and residue retention levels was computed based on the production costs and income from the sale of rice and maize grain, and rice stubble and maize stover. The production costs involved input costs, machinery costs, and labour used for the experiment. The cost of seed, growing the seedlings, fertilizers, insecticides, herbicides, and irrigation was considered as input costs; whereas machinery costs included a multi-crop planter and power tiller hired for tillage and seed sowing. The labour costs involved different operations, e.g., tillage, seedbed preparation, sowing/transplanting, irrigation management, thinning, weeding, harvesting and threshing. Gross returns (GR) were estimated by multiplying grain and straw yield by the price of grain and straw per hectare each year. The net income was calculated by subtracting the total input costs from the gross return and the gross margin was estimated by subtracting the total production cost from the gross return. The benefit-cost ratio (BCR) was computed as the gross return divided by the cost of production. All the prices were converted to US$ based on a conversion rate of 85BDT = 1 US$ (www.xe.com).

## 2.10 Statistical analysis

All data were analyzed statistically using a two-way factorial model based on a split-plot design (Popat and Banakara, 2020). In our study, as all the data were normally distributed ($p > 0.05$), they were exposed to parametric tests. The variables of the effects of different treatments were tested by analysis of variance (ANOVA), and comparisons between the treatments based on the least significant difference at $p \leq 0.05$. Before doing statistical analysis, the normality assumption of analysis of variance (ANOVA) was tested by Shapiro and Wilk (1965) by R Core Team (2020) and STAR statistical software (Biometrics and Breeding Informatics, PBGB Division, International Rice Research Institute, Los Baños, Laguna). In addition, the Conformity of homogeneity of variance was also tested by Bartlett's test (Snedecor and Cochran, 1989). Since the normality assumption of ANOVA was met, there was no need for data transformation. The effect of the treatment PTR/CTM vs. STDSR/STM was compared using *t*-test for independent samples (using STAR software).

# 3 Results

## 3.1 Effect on soil physical properties

### 3.1.1 Soil bulk density

The effects of TCE and crop residue management practices on soil bulk density (BD) were significant at 0–10 and 10–20 cm profile depths (Table 3). The ANOVA showed that, at 0–10 cm soil depth, the effects of TCE techniques on bulk density was lower by 2.73% in STDSR/STM compared to PTR/CTM. At the same depth, irrespective of residue management practices, the soil bulk density under TCE was lower than with no crop residue retention by 2% (4%) in 25% (50%) crop residue retention plots. On the other hand, in sub-surface soil (10–20 cm), PTR/CTM had a higher value (1.53) than STDSR/STM (1.49) considering TCE techniques. A similar trend was also found concerning residue management practices and a lower value was obtained in 50% crop residue retention treatment (1.49), followed by 25% crop residue (1.51) and no residue retention treatments (1.54). In addition, BD in soils under TCE and crop residue management practices increased with increasing soil profile depths. However, the ANOVA showed no significant interaction effect on TCE and residue management practices on BD in the 0–10 and 10–20 cm soil depths but the value of STDSR/STM with residue incorporation/retention plots declined at both depths.

### 3.1.2 Soil penetration resistance (SPR)

The main effects of TCE techniques and residue management were significant on SPR at 0–10 and 10–20 cm soil depths (Figure 4). SPR showed a tendency to increase at a depth of 0–10 cm and was always higher in PTR (333 kpa) than in DSR (ST) systems considering tillage practices. Furthermore, retention of residue caused a significant reduction in SPR compared to the residue removal plots, and the maximum SPR (366.01 kpa) was obtained in no crop residue retention followed by 25% crop residue retention (283.50 kpa). The lowest SPR (243.33 kpa) was recorded in 50% crop residue retention. At the same depth, irrespective of conventional and strip tillage with residue management practices, a significant effect on SPR was found in no and 50% crop residue retention, respectively. At a 10–20 cm depth, TCE techniques showed no significant effect on SPR, whereas a 16% reduction in SPR was recorded in STDSR/STM compared to PTR/CTM. At the same depth, mean SPR under 25 and 50% crop residue retention in STDSR/STM plots compared to no crop residue retention in PTR/CTM plot was reduced by 24 and 29%, respectively. In

TABLE 3 Soil bulk density (Mg $m^{-3}$) at two soil depths under different tillage and crop establishment (TCE) techniques and residue management (R) options at the end of 2 years of the rice-maize system.

| Parameters | 0–10 cm | | | | 10–20 cm | | | |
|---|---|---|---|---|---|---|---|---|
| TCE technique | CR0 | CR25 | CR50 | Mean | CR0 | CR525 | CR50 | Mean |
| STDSR/STM | 1.49 | 1.47 | 1.43 | 1.46b | 1.53 | 1.49 | 1.47 | 1.49b |
| PTR/CTM | 1.53 | 1.50 | 1.47 | 1.50a | 1.56 | 1.52 | 1.51 | 1.53a |
| Mean | 1.51a | 1.48b | 1.45c | | 1.54a | 1.51b | 1.49b | |
| LSD (0.05) | TCE = 0.025 | | | | TCE = 0.019 | | | |
| | Residue (R) = 0.01 | | | | Residue (R) = 0.02 | | | |
| | TCE × R = ns | | | | TCE × R = ns | | | |

Treatment details are in Table 2 and ns indicates no significant.

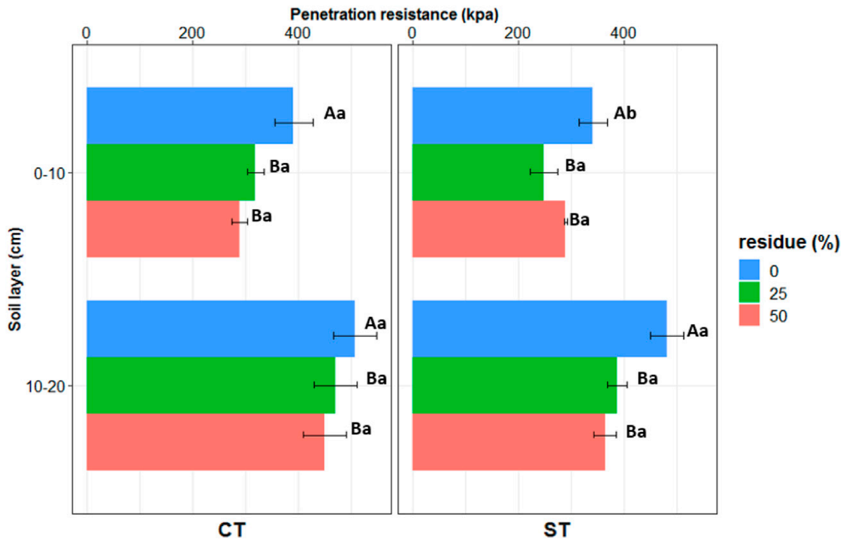


FIGURE 4
Effect of tillage and crop establishment (TCE) techniques and residue management (R) options on soil penetration resistance (KPa) at 0–10 and 10–20 cm profile depths at maize harvest in 2020–21. For treatment, details refer to Table 2. Different upper-case letters represent significant intragroup statistical difference at $p \le 0.05$; Different lower-case letters represent significant intergroup statistical difference at $p \le 0.05$; $p$ values calculated by the ANOVA test and $t$-test.

addition, at the same depth SPR values were 13 and 17% lower in 25 and 50% crop residue retention plots compared to no crop residue retention plots. The changes in SPR were positively correlated with BD at both depths. In our study, there was no significant differences between conventional and strip tillage at a 10–20 cm soil depth. Our study also found that 61% variation in SPR could be explained through BD; SPR = 1,452.3BD - 1854.2, $R^2 = 0.61^{***}$, $p \le 0.001$.

In comparison to two tillage methods with the same amount of crop residue retention, the mean SPR values in PTR/CTM plots were 14–46% higher under 0, 25, and 50% crop residue retention compared to STDSR/STM plots at 0–10 cm soil depth and by 23–26% at 10–20 cm soil depth (Figure 4).

### 3.1.3 Soil moisture content (SMC)

The ANOVA showed no significant interaction effect of TCE and residue management practices on soil moisture content (SMC) in the 0–10 and 10–20 cm soil depths. But the effects of residue management on SMC were, however significant at 0–10 cm and 10–20 cm profile depths. At a 0–10 cm depth, SMC increased by 7 and 17% under 25 and 50% crop residue retention plots compared to no residue plots. Besides, the effects of TCE techniques on SMC were not significant but it was increased by 10% in STDSR/STM compared to PTR/CTM (Supplementary Table S1). At a 10–20 cm depth, SMC was higher by 34% in STDSR/STM compared to PTR/CTM plots. At the same depth, SMC values were 8 and 15% higher in 25 and 50% crop residue

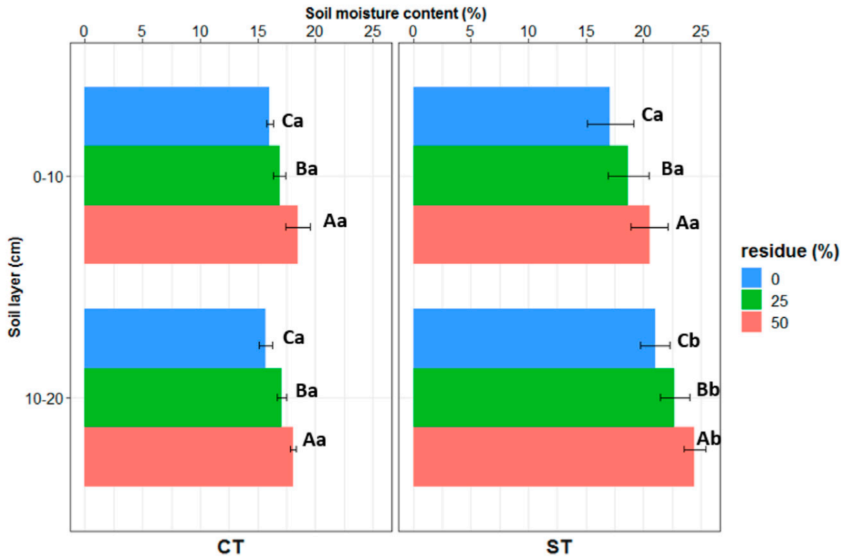


FIGURE 5
Effect of tillage and crop establishment (TCE) techniques and residue management (R) options on soil moisture content (SMC) at 0–10 and 10–20 cm profile depths at maize harvest in 2020–21. For treatment, details refer to Table 2. Different upper-case letters represent significant intragroup statistical difference at $p \leq 0.05$; Different lower-case letters represent significant intergroup statistical difference at $p \leq 0.05$; $p$ values calculated by the ANOVA test and $t$-test.

retention plots compared to no crop residue retention plots. There was a significant effect on SMC in the STDSR/STM and PTR/CTM plots, irrespective of residue management at 10–20 cm depth only (Figure 5). In our study, SMC was inversely correlated to SPR in both soil depths (r = −0.51, $p \leq 0.01$). When comparing two tillage systems with the same level of crop residue retention, the mean SMC values were 6–11% higher in STDSR/STM plots than in PTR/CTM plots at 0–10 cm soil depth and 32–35% higher at 10–20 cm soil depth (Figure 5).

### 3.1.4 Soil porosity

The effect of residue management practices was significant at both depths. At the 0–10 cm depth, the porosity value was higher by 9 and 18 in 25 and 50% crop residue retention plots compared to no crop residue retention plots. On the other hand, in sub-surface soil (10–20 cm) a similar trend was also observed and the value was 8 and 17% greater under 25 and 50% crop residue retention treatments compared to no residue retained/incorporation treatments. As compared to the conventional and strip tillage with residue management practices, there was a significant effect on soil porosity in the 50% crop residue retention plots at a 10–20 cm depth only (Figure 6). There was no interaction effect of TCE and residue management practices on soil porosity at 0–10 and 10–20 cm profile depths but the value was higher in the SDSR/STM plots (Supplementary Table S2). Mean soil porosity values were 11–45% higher under no 25 and 50% crop residue retention in STDSR/STM plots compared to PTR/CTM plots at 0–10 cm soil depth and by 11–12% at 10–20 cm soil depth.

## 3.2 Carbon fractionation

### 3.2.1. Dissolved organic carbon

In the present research, tillage management practises had the greatest influence on dissolved organic carbon (DOC) content (Table 4). The amounts of DOC were significantly higher in STDSR/STM management plots (38.73 mg $kg^{-1}$) compared to no residue retention plots (19.69 mg $kg^{-1}$) at a 0–10 cm depth. Irrespective of residue and tillage interaction plots, the value was higher in STDSR/STM practices under 25 and 50% residue retention/incorporation plots. Similarly, at 10–20 cm depth, a higher value (64%) was obtained in STDSR/STM practices compared to no residue retention practices. Considering, residue management practices, in both of the years, a higher value was observed in 25 and 50% residue retention/incorporation plots than no residue retention plots (Table 4).

### 3.2.2 Carbon stock in fractionation contributed by light, heavy POM and MAOM

The amounts of carbon in light POM present in the 50% residue retention/incorporation plots was 25% higher

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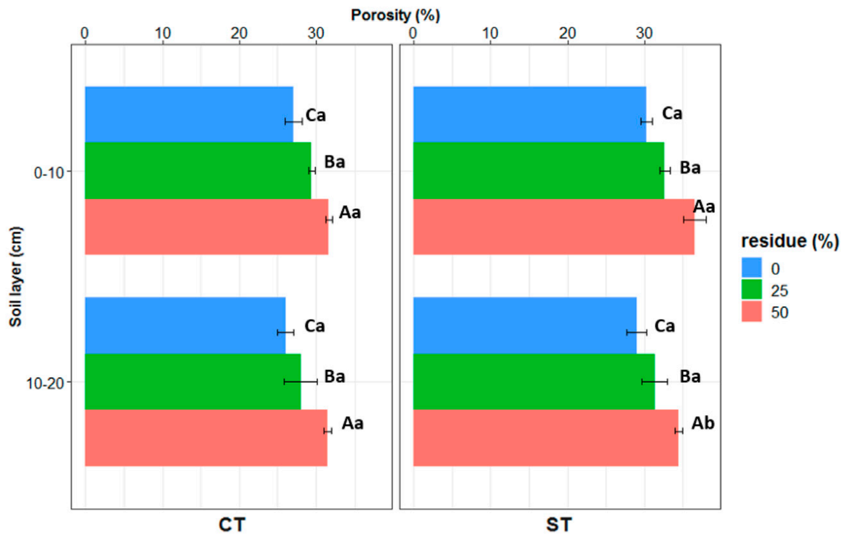


FIGURE 6
Effect of tillage and crop establishment (TCE) techniques and residue management (R) options on soil porosity at 0–10 and 10–20 cm profile depths. For treatment, details refer to Table 2. Different upper-case letters represent significant intragroup statistical difference at $p \leq 0.05$; Different lower-case letters represent significant intergroup statistical difference at $p \leq 0.05$; $p$ values calculated by the ANOVA test and $t$-test.

TABLE 4 Quantity of carbon in dissolved organic carbon (DOC) (mg kg$^{-1}$).

| TCE technique | 0–10 cm | | | | 10–20 cm | | | |
|---|---|---|---|---|---|---|---|---|
| | CR0 | CR25 | CR50 | Mean | CR0 | CR525 | CR50 | Mean |
| STDSR/STM | 37.45 | 39.45 | 39.28 | 38.73a | 42.55 | 46.09 | 48.25 | 45.63 |
| PTR/CTM | 19.09 | 20.27 | 19.70 | 19.69b | 21.52 | 36.87 | 24.97 | 27.79 |
| Mean | 28.27 | 29.86 | 29.49 | | 32.04 | 41.48 | 36.61 | |
| LSD (0.05) | TCE = 10.04 | | | | TCE = ns | | | |
| | Residue (R) = ns | | | | Residue (R) = ns | | | |
| | TCE×R = ns | | | | TCE×R = ns | | | |

Treatment details are in Table 2 and ns indicates no significant.

compared to no residue retained plots However, irrespective of residue level, the trend was higher in STDSR/STM plots at both depths. In sub-surface soil at a depth of 10–20 cm, the proportion of carbon provided by light POM was 28.7% higher in 50% residue plots than in residue removal plots (Figure 7).

Although no significant variation was observed in tillage practices, the value was 10% higher in strip tillage compared to conventional tillage practices. For the carbon stock in light POM, 50% crop residue gave better results compared to other treatments, as demonstrated by the highest amounts of SOC compared with the other residue management practices at a 10–20 cm depth ($p \leq 0.05$) (Figure 8). However, irrespective of residue levels, there was no significant difference but the value was 10% higher in strip-tillage than in conventional tillage. The interaction effect between tillage and residue management practices was not significant but greater values were observed in the STDSR/STM plots (Supplementary Table S3).

Our study showed that the SOC was higher in surface soil compared to the subsurface soil (Figure 8 and Supplementary Table S4) and a higher value was found in 25 and 50% residue plots than in no residue plots. The proportion of carbon contributed by heavy POM was 29% in surface soil and 14% in subsurface soil and the value was higher in 50% residue plots than in residue removal plots (Figure 7). We did not find any

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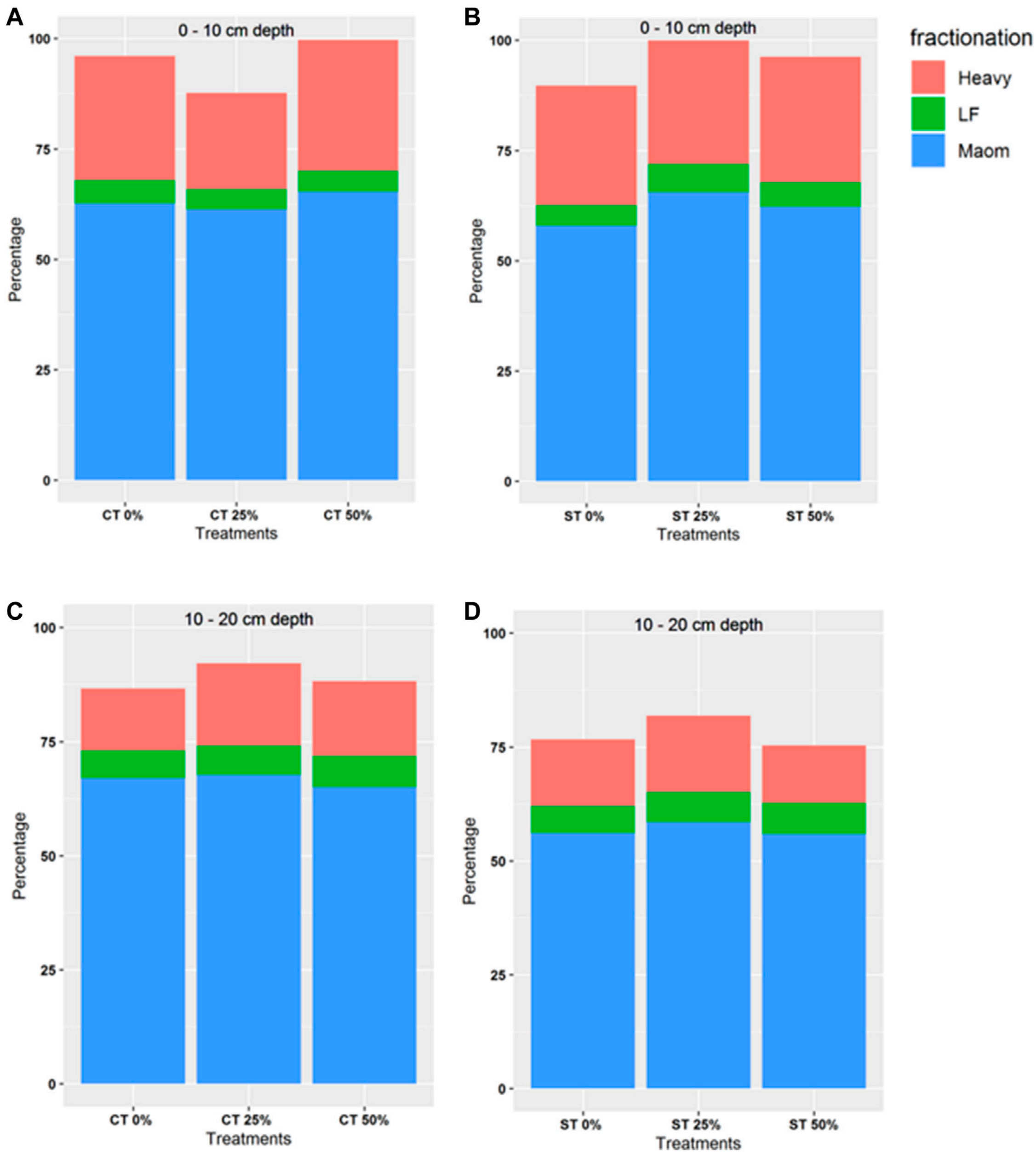


FIGURE 7
The proportion of carbon contributed by light POM, heavy POM and MAOM at 0–10 **(A,B)** and 10–20 **(C,D)** cm soil depths.

significant difference between tillage and residue interaction effect (Supplementary Table S4).

The effect of residue management practices was significant in surface soil. At the 0–10 cm depth, the carbon stock was higher by 27 and 8% in 25 and 50% crop residue retention plots compared to no crop residue retention plots (Figure 8). On the other hand, a similar trend was also observed in sub-surface soil (10–20 cm). Irrespective of tillage management practices, the higher carbon stock value was found in STDSR/STM plots (9.03 Mg $ha^{-1}$) compared to PTR/CTM plots (8.59 Mg $ha^{-1}$). The percentage of SOC stock that resided in the MAOM fraction and the value was 64 and 71% in 25 and 50% residue retention plots compared to the no residue plots (60%) (Figure 7). The ANOVA showed that there were no significant interaction effects between tillage and crop establishment (TCE) technique with residue management practices on carbon stock at 0–10 and 10–20 cm profile depths. But the value was higher in strip tillage with 50% residue

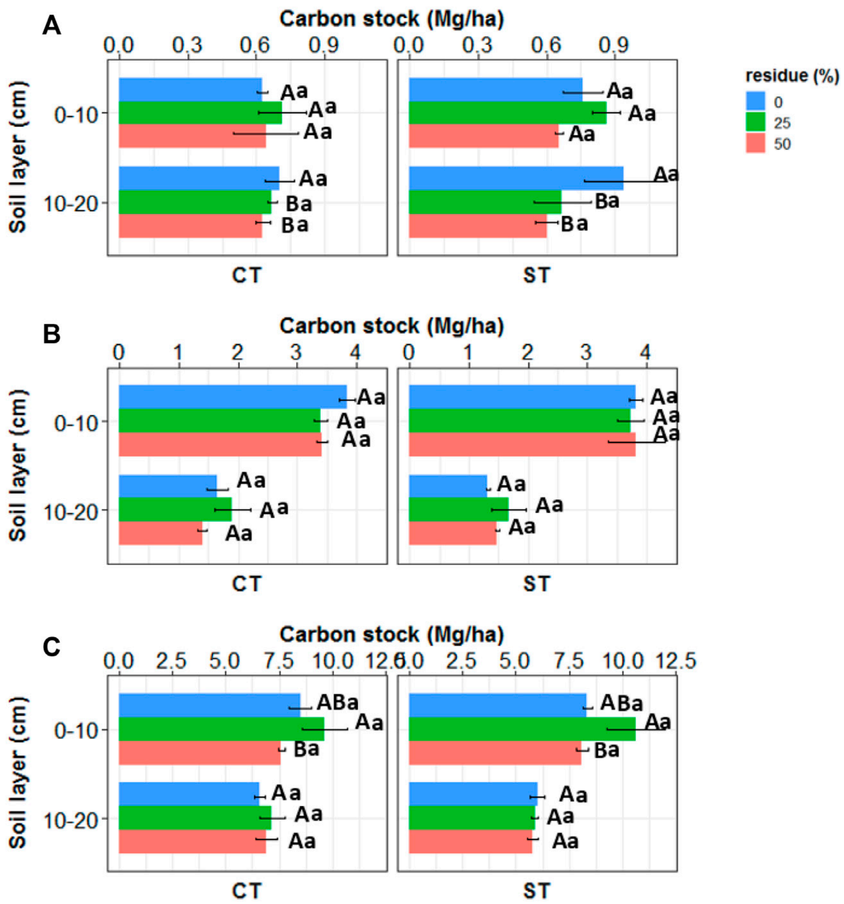


FIGURE 8
Carbon stock in fractionation contributed by light POM **(A)**, heavy POM **(B)** and MAOM **(C)** at 0–10 and 10–20 cm profile depths at maize harvest in 2020–21. For treatment, details refer to Table 2. Different upper-case letters represent significant intragroup statistical difference at $p \le 0.05$; Different lower-case letters represent significant intergroup statistical difference at $p \le 0.05$; $p$ values calculated by the ANOVA test and $t$-test.

retention plots compared to conventional tillage with no residue plots (Supplementary Table S5).

## 3.3 *Effect* of tillage and residue management on microbial biomass carbon (MBC)

### 3.3.1 Microbial biomass carbon (MBC)

The MBC was significantly higher under residue retention compared to no residue retention at both of the depths. At the depth of 0–5 cm, retention of 25 and 50% residues resulted in 45–54% higher MBC than no residue retention, whereas 37–41% was found at the 5–10 cm depth. Overall, there was a tendency for the values to be lower at the 5–10 cm depth. Moreover, we did not get an interaction effect ($p \le 0.05$) with tillage and residue practices on microbial biomass carbon (Supplementary Table S6). The result showed that there was no significant difference between two tillage systems with the same level of crop residue retention on MBC but the mean MBC values were 4–17% higher in STDSR/STM plots than in PTR/CTM plots for 25 and 50% crop residue retention at 0–5 cm soil depth (Figure 9).

## 3.4 Physiological parameters

### 3.4.1 Chlorophyll concentration

#### 3.4.1.1 Rice

In the first year, there was no significant variation in SPAD under crop establishment (TCE) techniques and residue management practices in different rice stages; 50, 60, 70, and 80 days after sowing (DAS) as shown in (Supplementary Table S7). However, higher SPAD values were observed in 60 DAS and the value was lower in 80 DAS. In the second year, the value was higher in

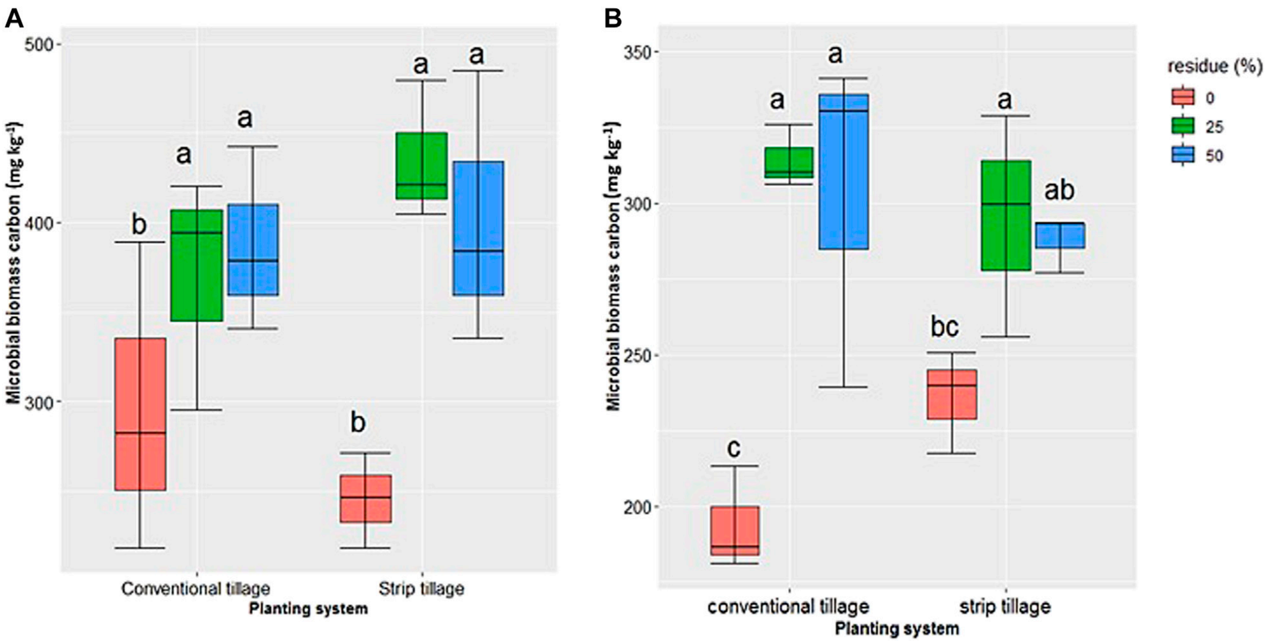


FIGURE 9
Allocation of microbial biomass at 0–5 cm **(A)** and 5–10 cm **(B)** depths as influenced by residue retention, and tillage-based crop establishment practices after 2-year of rice-maize system.

25 and 50% crop residue retention plots than in the 0% residue retention plots (Supplementary Table S8). The SPAD values decreased and varied from 38.7 to 31.4 (relative content of chlorophyll) in the no residue retention practices.

#### 3.4.1.2 Maize

In the first year of our study, there was significant variation in the effects of residue management practices in 90 DAS as shown in Supplementary Table S9. The maximum SPAD value (61.20) was recorded in 50% crop residue retention plots followed by 25% crop residue retention (59.39). On the other hand, the lowest values were found in no residue retention practice plots (57.56). Similarly, in the second year, the effects of TCE techniques and residue management practices were significant in 90 DAS and the maximum values were obtained in ST (57.26) rather than in PTR systems (56.30), as shown in (Supplementary Table S10). Irrespective of residue management practices, 50%, and 25% of crop residue retention plots showed higher values (57.38 and 56.03) compared to the no residue plots. However, in both the years, the interaction effects of crop establishment (TCE) techniques and residue management practices were non-significant ($p \leq 0.05$) during the growing period of maize but STM gave a higher value than residue removal plots.

## 3.5 The effect of tillage and residue management on yield component and cropping system

### 3.5.1 Yield and yield parameter of rice and maize

In the first year, there was no significant TCE × residue management interaction effect on the yield and contributing characters of rice. In our study (tiller/hill and panicle length) of rice were significantly affected by TCE techniques. However, PTR (CT) had 8 and 2% higher values in relation to panicle density and panicle length (cm) than DSR (ST) plots. Considering the yield, the trend was higher in PTR plots than in ST plots (Supplementary Table S11). Similarly, in the second year ANOVA also showed no significant interaction effects residue × TCE techniques on rice yield. The main effects were observed in tillage management practices, the yield being 14% higher in PTR compared to DSR (ST) plots. In both seasons, the biomass yield followed a similar trend to grain yield (Supplementary Table S12).

For maize, during 2019, 2020, the main effects of TCE practices were plant height and thousand-grain weight while other effects from residue management were recorded from grains/cob, 1,000 grain weight, cob length, cob line, and cob round. A decrease in plant height and weight of 1,000 grain weight in the order of 3 and 5% were observed in CTM after PTR compared to STM after STDSR. Retention of crop residues

TABLE 5 Rice and maize grain yields and rice equivalent yield (REY) ($Mg\ ha^{-1}$) in Rice-Maize cropping systems during 2019–2020 and 20–21.

| Items | Residues | Year 1 | | | | Year 2 | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | STDSR/STM | PTR/CTM | Mean | Summary | STDSR/STM | PTR/CTM | Mean | Summary |
| Rice | CR0 | 4.15 | 4.27 | 4.21 | LSD0.05 | 4.02 | 4.65 | 4.33 | LSD0.05 |
| | CR25 | 4.26 | 4.34 | 4.30 | TCE = ns | 4.21 | 4.72 | 4.47 | TCE = 0.30 |
| | CR50 | 4.25 | 4.35 | 4.29 | Residue (R) = ns | 4.12 | 4.78 | 4.45 | Residue (R) = ns |
| | Mean | 4.22 | 4.32 | | TCE×R = ns | 4.12b | 4.71a | | TCE×R = ns |
| Maize | CR0 | 8.44 | 8.29 | 8.37b | LSD0.05 | 9.07 | 8.32 | 8.67 b | LSD0.05 |
| | CR25 | 8.80 | 8.89 | 8.85a | TCE = ns | 9.68 | 9.43 | 9.55 a | TCE = ns |
| | CR50 | 9.21 | 9.08 | 9.14a | Residue (R) = 0.37 | 10.02 | 9.77 | 9.90 a | Residue (R) = 0.34 |
| | Mean | 8.82 | 8.75 | | TCE×R = ns | 9.57 | 9.17 | | TCE×R = ns |
| REY | CR0 | 9.48 | 9.65 | 9.56b | LSD0.05 | 10.30 | 9.51 | 9.91b | LSD0.05 |
| | CR25 | 10.16 | 10.06 | 10.11b | TCE = ns | 11.07 | 10.77 | 10.92a | TCE = ns |
| | CR50 | 10.37 | 10.52 | 10.45a | Residue (R) = 0.39 | 11.45 | 11.17 | 11.31a | Residue (R) = 0.39 |
| | Mean | 10.00 | 10.08 | | TCE×R = ns | 10.94 | 10.48 | | TCE×R = ns |

Treatment details are in Table 2 and ns indicates no significant.

increases the grains $cob^{-1}$ by 3 and 4%, 1,000 grain weight by 5 and 9%, cob length (cm) by 9 and 21%, in the case of 25 and 50% crop residue retention rather than no residue retention plots. The highest maize yield was recorded from 50% crop residue retention (9.14 $Mg\ ha^{-1}$) followed by 25% residue retention (8.85 $Mg\ ha^{-1}$), and the lowest was found from no residue treatment (8.37 $Mg\ ha^{-1}$), although there was no significant effect of the TCE practices on maize yield (Supplementary Table S13). In 2020, 2021, the trend of cobs $plant^{-1}$, grains/cob, weight of 1,000 grains, cob length, cob line, and cob round were similar to the previous maize crop. However, there was an increase in grains/cob (3 and 6%), the weight of 1,000 grains (4 and 8%), cob length (7 and 19%), cob round (2 and 6%) in relation to 25 and 50% crop residue retention compared to no residue retention plots. The trend in maize yield was similar to the previous season for TCE and residue management practices, and there was also a higher yield of 10 and 14% under 25 and 50% residue retention compared to no residue management practices (Supplementary Table S14). In both seasons, the biomass yields also followed a similar trend to grain yield. The present study did not find any significant interaction effect between tillage and residue practice but the yield was higher in STM plots compared to CTM plots.

### 3.5.2 Rice-maize system productivity

The total rice equivalent yield (REY) of the R-M system ranged from 9.56 to 10.46 $Mg\ ha^{-1}$ in the first year, while in the second year, it was 9.91–11.31 $Mg\ ha^{-1}$. Residue retention/incorporation practices resulted in consistently higher REY yields across the years. However, the highest system productivity was obtained from 50% crop residue retention practices (10.45 $Mg\ ha^{-1}$in year 1, 11.31 $Mg\ ha^{-1}$ in year 2) followed by 25% crop residue retention management (10.16, 10.92 $Mg\ ha^{-1}$). The lowest REY was recorded from no residue retention practices in year 1 and year 2 (9.56 and 9.91 $Mg\ ha^{-1}$). The incremental decline in REY was significant when crop residue was removed, with no significant difference when compared with the TCE technique. Overall, in year 1, the REY was higher at 5 and 9% under 25 and 50% residue retention compared to no residue management practices while it was 10 and 14% in year 2 (Table 5).

## 3.6 Gross margin analysis

In 2019, 2020, the effect of residue management was significant in relation to production costs, gross return, gross margin, and BCR but in the TCE technique (tillage practices) only production costs were significant in the RM system. The production costs were US$216 higher for PTR/CTM compared to STDSR/STM (Figure 10). Irrespective of residue retention, the production cost was highest (US$1,557) in CR0 while it was lowest (US$1,527) in CR50. Total gross return, gross margin, and benefit-cost ratio (BCR) are also highest in 50% crop residue retention treatments and lowest for no crop residue retention plots.

In 2021, 2022, there was significant variation in the main effects of TCE techniques and residue management practices relating to production costs, gross margin, and BCR in the RM system. The highest production cost (US$1,678) was found from PTR/CTM and the STDSR/STM gave the lowest production cost (US$1,462), as shown in (Figure 10). In the R-M system, the highest gross margin (US$1,696) and BCR (2.15) were also

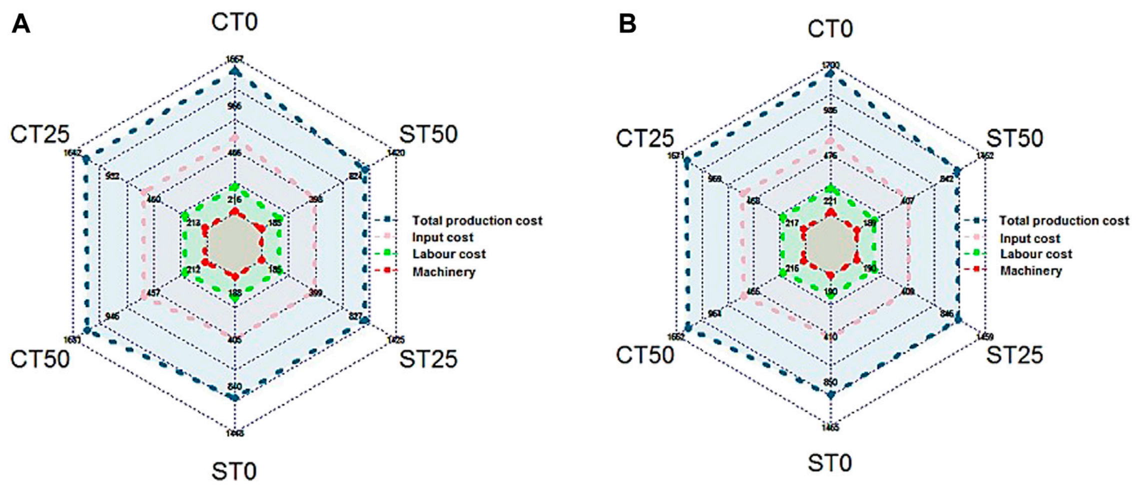


FIGURE 10
Cost of production under TCE techniques with residue management options for rice and maize system in northwest Bangladesh (CT0 = conventional tillage with no residue; CT25 = conventional tillage with 25% residue; CT50 = conventional tillage with 50% residue; ST0 = Strip tillage with no residue; ST25 = Strip tillage with 25% residue; ST50 = Strip tillage with 50% residue during 2019–2020 **(A)** and 2020–2021**(B)**. Numbers in each spider diagram mention amount in US$.

**TABLE 6** Economics of different crop establishment techniques and residue management options in rice-maize cropping system during 2019–2020 and 2020–21.

| Treatment/year | Production cost ($ ha$^{-1}$) | Gross return ($ ha$^{-1}$) | Gross margin ($ ha$^{-1}$) | Benefit cost ratio ($ ha$^{-1}$) |
|---|---|---|---|---|
| Year | 2019–2020 | | | |
| TCE technique (TCE) | | | | |
| STDSR/STM | 1431b | 3,003 | 1,573 | 2.09 |
| PTR/CTM | 1,647.a | 3,009 | 1,362 | 1.82 |
| Residue retention (R) | | | | |
| CR0 | 1,557 | 2893b | 1335b | 1.86 |
| CR25 | 1,533 | 3028a | 1494a | 1.98 |
| CR50 | 1,525 | 3097a | 1571a | 2.04 |
| LSD (0.05) | | | | |
| TCE | 22 | ns | ns | ns |
| Residue (R) | 3.42 | 113 | 115 | 0.08 |
| TCE×R | Ns | ns | ns | ns |
| Year | 2020–2021 | | | |
| STDSR/STM | 1467b | 3193a | 1696a | 2.15 a |
| PTR/CTM | 1678a | 3,163 a | 1515b | 1.90 b |
| CR0 | 1593a | 2,992 b | 1398b | 1.88b |
| CR25 | 1566b | 3233a | 1,666. a | 2.07a |
| CR50 | 1558c | 3,311 a | 1753. a | 2.13 a |
| LSD (0.05) | | | | |
| TCE | 30.58 | Ns | 145.06 | 0.08 |
| Residue (R) | 2.32 | 111.26 | 111.74 | 0.07 |
| TCE×R | ns | ns | ns | ns |

Treatment details are in Table 2 and ns indicates no significant.

recorded from STDSR/STM and the lowest was from the PTR/CT system (Table 6). The main effect of residue retention refers to gross return, gross margin, and BCR following the same trend in the previous year.

# 4 Discussion

## 4.1 The effect of tillage and residue management on soil physical properties

Soil penetration resistance (SPR) values were significantly lower in DSR (ST) than under PTR (CT) systems. Further, our results also showed an increase in SPR with an increase in soil depth. The key interpretation is that a higher SPR under PTR was related with a higher bulk density (especially at 10–20 cm depth) in these plots. This agrees with the results reported by Singh et al. (2016), who conducted an experiment in sandy loam soil with three tillage and two residue management options in the R-M system in north-west India and found that SPR showed an increasing trend with an increase in soil depth and was always higher in PTR (CT) compared to DSR (ZT) systems. Salahin et al. (2021) carried out a 3-year study in the Gangetic Plains of Bangladesh to evaluate the effects of zero tillage (ZT), strip tillage (ST), bed planting (BP), and conventional tillage (CT) with two residue retention levels. They found that the soil penetration resistance of the ST system was lower than that of the CT system. Lampurlanés and Cantero-Martínez (2003) also reported that increasing trend in SPR with an increase in soil depth. The higher SPR value in CT plots may be also associated with the development of plough pan at a 10–20 cm depth (Singh et al., 2013).

Irrespective of residue management practices, SPR was consistently lower in residue incorporation/retention plots compared to removal residue plots CT at 0–10, and 10–20 cm soil depths. The beneficial effect of incorporation/retention residue on PR is supported by Saha et al. (2010), who found that increased residue incorporation/retention reduced soil PR at a 0–15 cm depth on sandy loam soil. In a study in Uttar Pradesh, India, the continuous application of 5 Mg ha$^{-1}$ crop residues for 5 years in R-M systems decreased the SPR value by 23–31% over no residue plots (Singh et al., 2016). However, it is important to bear in mind that SPR is directly correlated to BD and inversely related to soil water content (Sharma and De Datta, 1986) and in our study, SPR also closely followed BD and soil moisture content trends. Jat et al. (2009) also reported that SPR had a greater value under puddling compared to ZT/conservation tillage.

The interaction effect of TCE techniques and residue on SPR was not significant in the present study. Similar observations were also reported by Singh et al. (2013), who conducted a long-term experiment to assess the effects of three tillage systems, no tillage (NT), ridge-tillage (RT) and plough tillage (PT), and three mulch rates (no residue, 8, and 16 Mg ha$^{-1}$ yr$^{-1}$ and reported that the interaction between tillage, mulch, and soil depth was not significant on SPR.

The present study demonstrated that the TCE technique's influence on bulk density and the value were lower in STDSR/STM compared to PTR/CTM at both depths. The main explanation is that puddling in rice crops is known to destroy soil aggregates and increase compaction of the soil (Gathala et al., 2011a). Our research also observed that strip tillage in DSR had a lower value compared to PTR (CT) treatment plots. This study is also in line with another researcher Singh et al. (2016) who observed that crop residue retention under DSR plots decreased soil bulk density compared to conventional tillage. In order to assess the impacts of zero tillage (ZT), strip tillage (ST), bed planting (BP), and conventional tillage (CT) with two residue retention levels, Salahin et al. (2021) conducted a 3-year research in the Gangetic Plains of Bangladesh. They discovered that the CT system had a larger bulk density near the soil surface than the ST system. According to a 4-year study in India by Gathala et al. (2011a), the CT-based system tends to have higher soil bulk density near the soil surface (10–20 cm soil depths) than the CA system.

In contrast, other researchers have found that higher bulk density under ZT at a 0–5 cm depth compared to CT in different cropping systems than R-M system (Wu et al., 1992; Gathala et al., 2011a; Huang et al., 2012; Jat et al., 2013). In our study, soil bulk density varied significantly due to residue management practices which is similar to the findings of He et al. (2009) who observed that crop residue retention under no-tillage practices decreased soil bulk density. The decreasing trend is strongly correlated with the deposition of organic matter and greater soil biological activity in ST practice (Alam et al., 2014). Moreover, Lal (2000) found that the incorporation of 16 Mg ha$^{-1}$ of rice residue for 3 years decreased BD from 1.20 to 0.98 Mg m$^{-3}$ on sandy loam soil. Coinciding with this result, Salahin et al. (2021) observed that soil BD did not significantly vary due to crop residue incorporation/retention practices. Sokolowski et al. (2020) observed that no-tillage practices increased soil BD compared to tillage systems (mouldboard plough) although the study was conducted in clay loam soil in an area with heavy rainfall. The present study also indicated that the interaction effects of TCE and crop residue management had no significant effect on soil BD. The findings is also confirmed by Singh et al. (2013) which reported that the interactive effect of tillage and mulch practices on soil BD was not significant in wheat crops. Our findings also differ from the results of Singh et al. (2016), who found interaction effects on the BD value at 0–15 cm and 15–30 cm depths.

Our study showed that strip tillage with residue retention/incorporation generated higher soil moisture content at all depths than in no residue plots. This is because residue retention in strip tillage maintaining favourable soil temperature by changing soil energy balances and heat fluxes (Kozak et al., 2007; Abdullah, 2014). In addition to this, another argument is that no residue with conventional tillage often creates the land unprotected from extreme temperature which in turn leads to a decrease in the amount of moisture contained in the soil (Ward et al., 2013). These findings are similar to Zhao et al. (2020) who conducted a meta-analysis to evaluate changes in SMC (soil moisture content), looking at CR retention in China (considering 278 publications), and observed that CRR (crop residue retention) led to an increase in SMC by 5.9% compared to CR removal. The present study also showed that higher SMC was found in strip tillage with residue retention compared to convention tillage with residue incorporation. The positive effect of retention residue on SMC is substantiated by Bhattacharyya et al. (2013), who performed a 6-years field experiment on sandy loam soil comparing various tillage methods with residues incorporated or retained on the soil surface. They discovered that areas where agricultural residues were retained on the surface included much more water-stable macroaggregates, which contributed to a higher SMC. Another example from Verhulst et al. (2011) who found that SMC was higher in residue retained plot due to less evaporation, which has an effect on SMC. A global meta-analysis by Li et al. (2019) indicated that CA-based management strategies increased accessible water by 10.2% higher than conventional practises. Many researchers agree that CA methods, such as strip tillage with the mulching effect of CR, are advantageous (Stewart et al., 2018; Lu, 2020). Other researchers Kader et al. (2017) also found that straw mulching helped to conserve soil moisture at a 0–30 cm depth and reduced soil temperature. The main explanation might be linked to lower soil temperatures and lower evaporation from residue retention plots (Busari et al., 2013). However, the trend of increased SMC owing to CA management practices is highly dependent on the regional climate (Abdallah et al., 2021). For example, Gathala et al. (2020) conducted a study in Bangladesh, Nepal and India and observed that water productivity was increased by 19% by adopting CA practices in the subtropical region. Consequently, negative outcomes were also found in cold -humid and tropical humid climates, where waterlogging was observed (Abdallah et al., 2021). The current study indicated that the retention of crop residue together with strip-tillage increased SMC compared to CT with the removal of residues. These results are similar to (Song et al., 2016) who found that removal of crop residue through conventional tillage causes soil water loss, thus affecting soil moisture content.

Soil porosity under CT was significantly lower than ST at two soil depths. The main explanation is that puddling in rice crops is known to increase compaction of the soil and ultimately reduces the porosity (Singh et al., 2016). Higher soil porosity under residue retention/incorporation in the plots than in soil with residue removal has been also reported by others (Alam et al., 2014; Alam et al., 2019). Another example from Patra et al. (2019) found that soil porosity was higher in zero tillage than in conventional tillage. These findings also in line with Liu et al. (2005), who observed that the retention of crop residue increased soil porosity when there was minimal tillage in the sub-surface layer. The increase of soil porosity in ST might be due to the addition of organic matter and crop residues which was the result of minimum soil disturbance (Alam et al., 2014). In contrast, Sasal et al. (2006) observed that total porosity was 3.5% higher in conventional tillage practices than in ZT-based practices in the surface soil layer (0–15 cm). Another example from Tangyuan et al. (2009) found that the total soil porosity was most affected in the surface layer rather than the sub-surface layer.

## 4.2 The effect of tillage and residue management on soil organic carbon fraction

The SOC fractions, like dissolved organic C, microbial biomass C and particulate organic matter C are known as a soil quality indicator parameter (Liu et al., 2014; Dong et al., 2009; Saviozzi et al., 2001; Lenka et al., 2015; Yang et al., 2005). As a relatively mobile fraction of the SOC, DOC plays an important role in the transport of nutrients, such as nitrogen and phosphorus (Kaiser, 2003). The current study revealed that the DOC in the 10–20 cm depth was higher in the TCE technique (ST) as compared to the CT soil. The strong stratification of the DOC at the 10–20 cm layer of the ST soil, due to receiving higher rainfall during the crop growing periods that may increase the downward movement of DOC to the deeper layer of soil. This is in line with Roy et al. (2022), who observed that surface drip irrigation increased the moist soil environment which is closely associated with a downward movement of DOC to a deeper layer. In coarse texture soil, a lower amount of clay content also contributed to this process (Gmach et al., 2019). Our results also showed that strip-tillage with direct-seeded rice plots have higher DOC, as compared to CT practices. The fundamental reason is that CT methods expose SOC to air, leading to increased organic carbon oxidation, whereas reducing tillage management practices favour organic carbon build-up under zero or reduced tillage (Zhao et al., 2015).

The study also observed a higher SOC stock in light POM in higher residue retention plots. It might be due to the mixing of crop stubbles and roots with soil which ultimately results in higher SOC stock. Our findings corroborate those of many other researchers (Blanco-Canqui and Lal, 2007; Liang et al., 2007; Nobuhisa and Hiroyuki, 2009). Liu et al. (2014) reported that improved crop management practices, such as no-tillage and residue retention/incorporation practices, often lead to an increase in SOC and SOC fractions compared to CT. Another example from Chivenge et al. (2007), found that higher SOC was obtained from sandy soils in plots where mulch ripping with residue retention was practiced compared with plots where clean ripping was carried out with no residue retention.

In heavy POM, the beneficial effect of strip tillage and crop residue retention/incorporation on SOC stock was recorded only in the 0–10 cm soil layer, but not in lower layers (Figure 8). These findings are also similar to Luo et al. (2010) who observed that SOC stock was higher in ZT plots only in the upper surface layer (0–10 cm), but decreased by 3.30 ± 1.61 Mg $ha^{-1}$ at a lower depth (20–40 cm) over CT practices. Roy et al. (2022) also reported that higher SOC stock was observed at the surface layer followed by lower SOC stock in the subsurface soil layer in CA-based practices compared to conventional practices. Based on a short-term study (2-year trial) in Bangladesh, Chaki AK. et al. (2021) discovered that the CA-based system tended to have greater soil TOC near the soil surface (0–5 cm and 5–15 cm soil depths) than the CT system. Moreover, This was also well supported by Zeng et al. (2021) who recorded a higher SOC in the top layer of soils than in the sub-layer soils. The key management difference across the treatments that could explain the greater SOC stock in the STDSR/CMT was the addition of residue of 4.2 Mg $ha^{-1}$ $year^{-1}$ (Figure 8 and Supplementary Table S15). According to Bhattacharyya et al. (2015), CA practices boosted both SOC content and stock as compared to CT. Similarly, the residue retention plot produced a much larger SOC stock (6 Mg/ha/year), according to (Ranaivoson et al., 2017).

Crop residue can play an important role to increasing and/or maintaining SOC levels in the soil profile although its effect may be influenced by how residue is kept in the soil, e.g., residue surface retention vs incorporation (Turmel et al., 2015). When comparing two tillage systems with the same level of crop residue retention, the study observed that SOC stock was higher under strip tillage with residue retention compared to conventional tillage with the incorporation of residue in the plot at the surface layer. The main explanation is that crop residue on the surface under strip tillage involves less interaction with soil microorganisms (Salinas-Garcia et al., 2001), and therefore decomposition is more gradual than CT, where residue comes into close contact with microorganisms when mixed in the soil (Reicosky et al., 1997). This finding is in line with Kuswaha et al. (2001) who conducted an experiment in India between residue retention vs. incorporation, and found that SOC is higher under minimal tillage with the residue retained in plots compared to incorporation in plots. Our findings are in agreement with other researchers who found higher SOC content in no tillage than reduced tillage (Singh et al., 2020). In contrast, Dong et al. (2009) conducted an experiment in Northern China and found that SOC content was higher in CT with residue incorporation treatment but the study was conducted in silt loamy soil. Moreover, Turmel et al. (2015) reported that there was a significant increase in SOC content in the CT with residue treatment plots. However, it is well understood that incorporating crop residues into the soil improves soil aeration, and temperature, and creates favourable conditions for microorganisms, resulting in higher decomposition rates and ultimately SOC loss (Coppens et al., 2007; Fontaine et al., 2007) particularly in sub-humid temperate to sub-humid tropical regions (Turmel et al., 2015). At 30°C, the rate of SOC mineralization can increase by up to 72–177%, according to Ghimire et al. (2019). In addition, Moldboard ploughing is generally shown to decrease C stocks in the soil (Turmel et al., 2015). However, our study confirmed that combining strip tillage with residue retention, either complete or partial on the surface, is more helpful than removing the residue entirely.

Because of the inconsistency of the findings of SOC in the soil under tillage and residue management practices, it is, therefore, recommended that the whole soil profile should be studied rather than shallow sampling (Vanden Bygaart and Angers, 2006). This will help to provide more accurate information on the effects of residue management practices on SOC in the soil (Baker et al., 2007).

## 4.3 The effect of tillage and residue management on microbial biomass carbon (MBC)

Soil microbiological indicators like MBC are influenced by land management practices and environmental changes (Zhao et al., 2018)Our study showed that strip tillage with residue retention/incorporation generated higher microbial biomass carbon (MBC) at all depths than in no residue retention plots. This is because the addition of residue increased soil organic carbon (Saurabh et al., 2021) and this gradually increased with increasing quantities of residue return, which ultimately promote soil MBC (Zhao et al., 2018). Another explanation for higher MBC could be that the residue provides readily mineralisable and hydrolysable carbon for better microbial growth (Samal et al., 2017). Moreover, the incorporation of crop residues into the soil may have a beneficial effect on endogeic (horizontal-burrowing) earthworms because it will act as a food source (Wuest et al., 2005). This is consistent with our observation that it influences the total organic C pool, due to changes in C supplied by crop residues, and ultimately that is reflected in the microbial biomass (Franzluebbers et al., 1999). The present study also observed that higher MBC were found on the surface than in the subsurface layers. The possible reason for this may be the lesser availability of crop residue at a lower soil depth. Moreover, another reason is that zero tillage with residue retention on the topsoil makes the soil cooler and wetter, resulting in lower fluctuations in moisture and temperature (Kaldivgo, 2001) and ultimately encouraging microbial substrates as well as higher MBC (Luna-guidoet al, 2007). Our findings are in agreement with many other researchers (Zhao et al., 2018; Chen et al., 2020). In addition, a reduction in the loss of SOC and a uniform supply of carbon from crop residues act as a source of energy for microorganisms (Kumar and Babalad, 2018). Our study also suggested that there was no significant effect between TCE techniques in relation to MBC. This result was confirmed by other research (Luna-guido et al., 2007) which found that zero tillage on its own does not provide higher MBC compared to zero tillage with residue retained. When comparing two tillage systems with the same level of crop residue retention, the study observed that MBC was higher under strip tillage with residue retention compared to conventional tillage with the incorporation of residue at the surface layer. This may be because microbial biomass was closely connected to the distribution of SOC and the amount of moisture in the soil (Doran, 1987; Salinas-Garcia et al., 2001).

## 4.4 The effect of tillage and residue management on physiological properties

The concentration of chlorophyll in the leaf is an important indicator that can be used to determine soil N supply to growing plants during the growing season (Mupangwa et al., 2020).

Our study showed that strip tillage with residue retention/incorporation generated higher SPAD values than in no residue retention plots. A higher SPAD value in the second year might be partly due to higher rainfall and the residue conserving the moisture. This finding is in line with other researchers (Liu and Wiatrak, 2012) who concluded that there was no significant difference between different tillage systems but found that the value was higher in the season with the highest rainfall. Other findings, for example, Najafinezhad et al. (2015) reported that drought stress reduced the concentration of leaf chlorophyll (SPAD value) by 5.21% compared to normal irrigation. Moreover, Shefazadeh et al. (2012) also found that the chlorophyll concentration in wheat leaves was highly correlated with the soil's moisture status. Reductions in chlorophyll might be due to the production of ROS (reactive oxygen species) under oxidative stress which ultimately leads to the degradation of chlorophyll pigments (Sairam and Srivastava, 2002). A decrease in the chlorophyll content was also reported in other crops when the supply of water and nitrogen was limited (Lauer and Boyer 1992; Paknejad et al., 2007; Massacci et al., 2008). In maize, our study showed that the retention of residue caused a significant increase in SPAD values compared to the removal of residue from the plots. These findings are also similar to Najafinezhad et al. (2015) who found that drought stress decreased total chlorophyll by 12.46% in the corn crop. The increase in SPAD value in the residue retention plots may be associated with the increase of moisture retention in the soil, resulting in the prevention of oxidative stress effects, and ultimately, it helps to overcome the harmful influences of drought stress on chlorophyll (Najafinezhad et al., 2015). An increase in chlorophyll content in barley crops by using 4.5 t $ha^{-1}$ residue has been reported by Najafinezhad et al. (2015) as well as in ridge tillage with mulching in winter wheat crops (Li et al., 2018).

## 4.5 The effect of tillage and residue recycling on crop yields and the cropping system

The results of the study demonstrated that STDSR gave lower yield compared to PTR. The lower yield of STDSR was associated with a lower number of panicles and reduced panicle length compared to PTR. Other possible reasons for a lower yield in DSR compared to PTR could be, 1) micronutrient deficiency (Fe and Zn) due to aerobic conditions (Singh et al., 2016) 2) increased weed and insect infestation (Gathala et al., 2011a) 3) moisture deficiency due to higher infiltration rates (Singh et al., 2016) and 4) the high plant density of DSR needs more mineral nutrients than PTR (Schnier et al., 1990). These findings are similar to Chaki AK. et al. (2021) who found that the mean decrease in rice yield was 0.83 t $ha^{-1}$ in zero tillage in comparison with PTR in light-textured soil. Similarly, Rashid et al. (2018), who conducted an experiment in light-textured soil in southern Bangladesh, also recorded a 3, 4% lower yield in ZT compared to PTR. In contrast, other studies conducted by Haque et al. (2016); Islam et al. (2019) and Saharawat et al. (2010) also compared the performance of PTR and ZT UPTR with fully irrigated conditions, where the ZT UPTR produced a higher yield than or similar yield to PTR. Therefore, there is a need to assess the dynamics of macro-and micronutrients in the soil to achieve an optimum rice yield when PTR is replaced by DSR. Although the DSR plots gave a lower yield, the shorter time the crops spent in the field in DSR (as DSR plots were harvested 7–10 days earlier than puddled transplanted rice (Saharawat et al., 2010) might create an opportunity for the timely planting of successional maize crops. However, despite the lower yields in DSR than in PTR, an aerobic rice system requires low input (water, labour, and fuel) (Farooq et al., 2011; Kumar and Ladha, 2011).

In our study, the TCE techniques with rice residue retention/incorporation of either 25% or 50% gave a higher maize yield compared to the removal of all residue from the plots. Our findings agree with Rashid et al. (2019) who concluded that compared with full straw removal, 50% straw retention increased the grain yield of maize by 5%, and Singh et al. (2016) who also reported that the maize yield under a ZTDSR/ZTM + R system was higher by 4.0 and 14.2% than CTDSR/CTM and PTR/CTM. The higher maize yield under residue retention/incorporation practices might be due to the utilization of mineral N by microorganisms, and in later seasons, increased the efficiency of available N uptake by nutrient recycling (Jat et al., 2012;

Alam et al., 2020). Moreover, the higher soil moisture concentrations under ST with residue retention practices are also likely to have contributed to the higher grain and biomass yield compared to conventional tillage practices (Asargew et al., 2022). In addition, the yield was increased in STM after DSR possibly due to avoiding puddling in rice (Hobbs et al., 2002; Gathala et al., 2011b; Jat et al., 2014), and the fact that the role of crop residues correlated with reducing the adverse impact of terminal heat stress during the reproductive phase (April and May), and provided an optimum soil thermal regime (STR), coupled with better root growth (Singh et al., 2016). Puddling (wet tillage) in rice forms a hard plough pan, increases the bulk density, disturbs the soil structure, fills the macropores with finer soil particles as well as reducing porosity and increasing soil compaction, which adversely affects upland crops (Sharma et al., 2003; Gathala et al., 2011a). These results are also consistent with the findings of another researcher, Singh et al. (2016) who recorded a higher yield in ZT (zero tilled) maize compared to that in CT plots. However, the meta-analysis conducted by Sun et al. (2020) found that semi-arid to humid regions, with $40 \leq HI < 100$, are good for CA-practices and have the potential to enhance SOC in soil (humidity index, “HI” (average rainfall/mean air temperature). The R-M system productivity (rice equivalent yields) generally followed the increasing trend with time, ranging from 5 to 9% in year 1 to 10–14% in year 2, when crop residue was retained/recycled. These findings are similar to Rashid et al. (2019) who concluded that the highest REY was found from residue retention compared with no retention plots.

## 4.6 The effect of tillage and residue management on profitability

The current study showed that the cost of production for R-M was higher in CTPTR/CTM compared to STDSR/STM practices due to the high labour and fuel costs of land preparation for maize, the high cost for transplanting rice seedlings and manually seeding maize crops. In our study, CTPTR practices required the highest (\$1,647 $ha^{-1}$) and STDSR/STM required the lowest input costs (~\$1,431 ha−1) in the rice maize system. There could be several explanations for higher production costs in CTPTR including 1) higher labour costs associated with activities such as land preparation, transplanting rice, sowing maize, irrigation *etc.*, under CTPTR/CTM practices, 2) machinery costs, especially for puddling which typically required tilling 4–6 times before transplanting rice and 3, 4 times before for sowing maize. Our findings are in agreement with others (Singh et al., 2014; Gathala et al., 2015; Rashid et al., 2019), who compared input costs, e.g., labour and the machinery required for PTR, and STDSR practices, where STDSR involved lower costs compared to PTR. In the current study, regardless of residue retention, the production cost in residue retention plots was lower than in no residue plots. This may be because crop residue cleanup and transportation on the farm needed more labour and fuel. These findings are similar to those of Sarkar et al. (2020), who observed that removal of crop residues required more labour, effort, and capital. The present study also showed a higher gross return, gross margin, and BCR under strip tillage with residue incorporation/retention than conventional tillage with no residue retention in the plots. This finding is similar to that of other researchers (Gathala et al., 2011b; Laik et al., 2014; Parihar et al., 2016; Rashid et al., 2019). Although such clear benefits were observed from TCE techniques with residue retention/incorporation, but the present study has some limitations for implementing these research findings in farmers’ fields as our analysis is based on data from a research station experiment on a small plot of 35 $m^2$. Our study suggests that economic analysis in the future could be conducted by research station experiments on larger plots.

## 4.7 Practical applications for climate change mitigation and future research

Given the current climate change issues, the implementation of a CA-based agricultural system is one of the most essential ways to decrease the expected increase of GHG emissions in the atmosphere. Since the CA-based systems improve soil health and organic carbon stocks by fostering soil carbon sequestration by incorporating crop residue and also minimum disturbance of soils. However, CA may not absorb more carbon over time than conventional systems if all CA principles, such as minimum soil disturbance, permanent soil organic cover with crop residues and/or cover crops and crops diversification are not followed properly. The current study revealed that crop residue retention is essential for enhancing soil organic carbon in R-M rotation. Providing incentives to farmers based on carbon footprint/storage and other ecosystem services through residue retention is a viable technique for encouraging the adoption of CA technology in tropical and temperate climatic regions. However, it is recognized that these results represent only 2 years of a field experiment, and a longer period of the study is needed to assess the performance of ZTDSR/ZTM with varying rates of crop residue mulch in R-M systems in diverse soil, climatic, and socio-economic conditions. Besides longer experiments, cropping system simulation studies accounting for the impact of climate change on soil and crop variables might be needed to give greater insights into the long-term impacts of tillage and residue management on sandy soil under R-M systems in Bangladesh.

## 5 Conclusion

Adoption of conservation agricultural techniques in the study areas has a tremendous effect on the crop profitability of farmers, particularly on sandy loam soils in North-Western Bangladesh. The sustainable intensification practices assessed in this study address the issue of declining soil fertility, especially the decline in organic carbon, microbial biomass carbon and increased soil compaction, *etc*. We found that strip tillage direct-seeded rice (STDSR), followed by strip-tilled maize (STM) with partial residue retention/incorporation (+R) from both the crops, improved SOC content and the soil's physical properties, namely soil bulk density, porosity, soil penetration resistance, soil moisture, and other soil and crop parameters, especially microbial biomass carbon and chlorophyll content. Our results showed a decrease in bulk density (4.3–6.9%) and penetration resistance (15.9–30.7%), and an increase in organic carbon (23.6–35.3%), soil moisture content (11.1–21.3%), and porosity (16.1–32.5%) compared to a conventional tillage-based rice-maize rotation in sandy soil. It was also observed that soil biological health, i.e., microbial biomass carbon (4–9%), and physiological parameters like leaf chlorophyll concentration, had significantly improved in STDSR/STM compared to PTR/CTM. Furthermore, puddling in rice with residue removal practices showed a negative impact on soil properties for maize production. The overall improvement in soil conditions resulted in gradually enhanced crop productivity, particularly for maize in ST plots, and improved farm profitability compared to conventionally tilled rice and maize crops. Therefore, to maintain soil health and high crop productivity, residue inputs should be combined with the use of appropriate tillage techniques. However, for organic matter to build up in sandy soil, more emphasis should be put on the addition of organic resources, such as keeping at least 25–50% of crop residues and incorporating them into the soil.

## 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

MS: Conceptualization, Methodology, Analysis, Data curation, Writing- original draft; MG: Supervision, Formal analysis, and editing; AnC: Supervision, Formal analysis, and editing and MH: Conducted experiment and data collection, ApC: Data collection and Visualization and AH: Visualization, and 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.

## Publisher's note



## Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2022.969819/full#supplementary-material

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# Rice farmers' perceptions about temperature and rainfall variations, respective adaptation measures, and determinants: Implications for sustainable farming systems

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In Pakistan, climate change is adversely affecting agricultural production and undermining the food security and subsistence of millions of farm households. Farmers' understanding of climate change and their adaptation strategies can serve as a useful step to help minimize climate risks. This study explores farmers' perception of and adaptation strategies to climate change and their determinants in the rice-growing zone of Punjab province, as this region of the country is highly vulnerable to climate change impacts. The multistage stratified-random sampling method was used to select 480 farmers from the four rice districts of the region, and data were collected using a structured questionnaire. Logistic regression and contingency tables are used to analyze the determinants of farmers' adopted strategies and adaptation extent (number of adopted strategies). Results show that farmers perceived significant changes in the climate, including the rise in average summer and winter temperatures and the decline in overall precipitation. The study further found that farmers' adopted adaptation strategies include supplementary irrigation, adjustments in rice cultivation dates, crop diversification, use of climate-smart varieties, better fertilizer management, and farm resizing. Logit model showed that farmers' age, primary occupation, income, landholding, access to irrigation, credit, climate information, and farm advisory appeared to be the significant determinants of their adaptation decision. The adaptation extent strongly correlates with farmers' education and access to climate information and credit services. Based on these findings, this study suggests the relevant institutions improve farmers' access to irrigation water, credit, farm advisory, and climate information to improve their adaptation extent and hence resilience of the rice-farming system.

KEYWORDS

Climate change, awareness, adaptation, socio-economic analysis, agriculture, Pakistan

## 1 Introduction

Inter-Governmental Panel on Climate Change (IPCC) predicts more frequent and severe climate events in the near future (Field et al., 2014). These indications will have severe consequences for different sectors of the global economy, including agriculture, and may undermine socio-economic development across the globe (Masud et al., 2017). The impact of climate variability and change on agriculture in the form of reduced crop yields, soil degradation, and water scarcity has posed a significant threat to livelihood and food security at both regional and global scales (Knox et al., 2012; Alauddin and Sarker, 2014). These impacts disproportionally affect developing countries' socio-economic development owing to their higher dependence on agriculture and related sectors (Fahad and Wang, 2018). South Asia is counted among the world's most vulnerable regions to climate change due to its high exposure to climate-induced risks and disasters (Field et al., 2014; Aryal et al., 2020). It is reported that a one-degree Celsius temperature rise may reduce cereal production in South Asia between 4%–10% by 2,100 (Aggarwal and Sivakumar, 2010; Lal, 2011). It is further shown that declining crop production may severely harm the food security of the region, where food production needs to be doubled by the end of this century (FAO FAOSTAT, 2016). The recent droughts in Nepal and Sri Lanka (Chandrasekara et al., 2021) are giving us a taste of what is to come when the consequences of climate change will be more widespread and more noticeable.

Like many countries in the region, Pakistan is facing the alarming challenge of climate-induced catastrophes. Pakistan is reportedly the world's fifth most vulnerable nation in terms of the long-term impacts of climate-induced disasters (Eckstein et al., 2019). This is caused by a significant temperature rise in the country during the past 6 decades; the average temperature has risen to half a degree Celsius (Chaudhry et al., 2009), triggering several disastrous events, such as floods, droughts, and biological hazards. Series of extreme droughts in the late 1990s to early 2000s (Khan et al., 2020a), four deadly floods between 2010–2014 and disastrous floods of 2022 (Shah et al., 2021; Sarkar, 2022), and a recent climate-led locust outbreak (Khatri, 2019) are a few examples. Such catastrophes are alarming for a developing nation like Pakistan, which mainly relies on agriculture and associated sectors that are highly sensitive to climatic variations.

In Pakistan, the agriculture sector contributes over 20% of the total Gross Domestic Product (GDP) and employs over 40% of its total labor force (Khan et al., 2020b). During the floods of 2010, Pakistan's agriculture sector faced a loss of over one million hectares of unharvested crops and 1.5 million livestock resulting in a loss of over US$10 billion to the poor economy (Shah et al., 2018). The recent flood of 2022 that wreaked havoc in Pakistan, washing out one-third of the country, displacing three million people, and causing unprecedented loss of human lives, crops, and livestock, is believed to be more disastrous than the historic 2010 floods, which is mainly caused by unexpected monsoon rainfall in the country (Sarkar, 2022). Such calamities are significant threats to people's livelihoods as agriculture provides subsistence to the millions of farm households in Pakistan. Among many crops, rice is reported as the most vulnerable food crop, facing a major yield decline due to the impacts of climate change and variability (Ahmad et al., 2015; Ali et al., 2017). In Punjab province alone, rice yield has declined by nearly 7% during the past decade (AMIS, 2018), mainly due to climate change-led water scarcity, increasing average temperature, and declining average precipitation. Studies have shown that rice production in Punjab is likely to decline further by up to 36% by the year 2099 if the current trend of climate change continues (Ahmad et al., 2015) and if farmers do not adequately adapt to the resultant impacts. Given the challenges to cereal crops, food security is being seen as an emerging challenge (Khan et al., 2021a). In this scenario, adapting agriculture to climate change is imperative to avoid existing and potential risks of yield decline.

Climate change adaptation is considered a useful strategy to address climate risks and their impact on the agriculture sector (Khanal et al., 2018a; Khan et al., 2021b). Farming systems and communities may adopt various adaptation strategies in the form of adjustments in cropping operations (Arunrat et al., 2017), adoption of improved farm management practices (Di Falco and Veronesi, 2013), and use of climate-smart seeds (Zhai et al., 2018; Sertse et al., 2021) to avoid the adverse effects of changing climate. The literature widely advocates the effectiveness of climate change adaptation measures in agriculture, making it one of the effective ways of tackling climate risks in agriculture (Khanal et al., 2018b; Sertse et al., 2021). For instance, studies in Africa widely report the use of climate-smart seeds, shuffling in crop planting dates, and water management practices among key strategies; Sertse et al. (2021) report climate-smart seeds to be one of the most useful strategies, and Amare et al. (2018) stated positive contribution of adaptation in terms of improving household food security. Similarly, a number of studies in Asia also suggest that farmers' adaptation measures are positive contributors to crop productivity; Khanal et al. (2018a) report rice farmers' adaptation strategies in Nepal which include soil and water management practices, shuffling of cultivation dates as effective strategies to deal with the variation of temperature and precipitation and a study in China (Cui and Xie, 2022) concludes that adjustments in crop planting dates can significantly avoid crop damages caused by climate change. Many types of adaptation strategies are widely discussed in both empirical and theoretical studies, such as ex-ante and ex-post adaptation (Abid et al., 2020) or autonomous and planned adaptation (Mersha and van Laerhoven, 2018; Khan et al., 2021c). Some studies distinguish adaptation in terms of time (anticipatory or reactive), type (technical, behavioral, or institutional), planning (short term or long term), and sector involved in managing or implementing it (Private or Public) (Bastakoti et al., 2017). Among various types, farm-level autonomous adaptation strategies are the most common form of adaptation that farming communities consider while facing climate risks (Arunrat et al., 2017; Masud et al., 2017). Previous studies (Adarsha et al., 2017; Khatri-Chhetri et al., 2017; Shah et al., 2022) show that the adoption of such adaptation strategies is mainly shaped by various attributes associated with farm households. These attributes include farmers' education, farming experience, farm assets, access to farm inputs, and, most importantly, availability of credit and information. Recent studies revealed that adaptation is largely shaped by farmers' contact with extension officers, daily media usage, availability of farm machinery, and membership in farmers' associations (Shahbaz et al., 2021; Ul Haq et al., 2021). Although a range of factors is discussed in these studies, important farm and economic attributes, such as farm labor availability, canal water availability, and primary income source, are not included in terms of their relationship with adaptation decisions, which this research intends to explore.

In Pakistan, the literature on climate change adaptation and agriculture is continuously growing, given the country's vulnerability to climate variations (Ali and Erenstein, 2017; Fahad and Wang, 2018; Hussain et al., 2020). For instance, Abid et al. (2015) conducted a study in the three agroecological zones of Punjab province and assessed that wheat farmers adopt a number of on-farm adaptation measures to cope with climate change, which are mainly associated with their socio-economic attributes. Similarly, Hussain et al. (2022), in their study in the southern part of Punjab province, assessed the impact of weather shocks on farmers' income and evaluated farm households' perceptions and coping strategies against weather shocks. Fahad and Wang (2018), on the other hand, assessed the vulnerability of farming communities in the Khyber Pakhtunkhwa province of Pakistan by exploring farmers' exposure to climate risks and their adaptive capacities. Similarly, some studies have also evaluated the efficacy of adaptation strategies; for instance, Ali et al. (2017) assessed the impact of climate change adaptation practices on household food security and poverty levels in different provinces in Pakistan. Despite the growing literature, empirical research still remains scarce, particularly, in the case of the major rice-growing region of the country, regarding the assessment of farm households' climate change perception, adaptation strategies, and socio-economic drivers of adaptation. Such empirical research on climate change adaptation and its determinants holds a fundamental significance in policy and action frameworks, as it outlines the current state of adaptive capacities of the farming systems and plays a pivotal role in designing relevant policies (Bonzanigo et al., 2016). Therefore, considering the research gap and significance, this study is particularly focused on the rice-growing zone of Punjab province, a region facing a decline in rice yield, and intends to explore how farmers perceive and adapt to climate change. Specifically, the study has three research objectives: 1) to assess rice growers' perceptions of climate change in the study area, 2) to explore farmers' adaptation strategies in the rice-farming systems, and 3) to analyze the factors affecting farmers' adoption of adaptation strategies.

# 2 Research methodology

## 2.1 Research site

This study was conducted in the Punjab province of Pakistan, which is a leading agricultural province in the country. Punjab contains over half of Pakistan's total cultivated land area and produces 70% of its cereal crops, generating over half of its agricultural GDP (Khan et al., 2020c). Punjab province is situated in the eastern part of the country, bordering India from the east, Sindh province from the South, and the provinces of Khyber Pakhtunkhwa and Baluchistan from the northwest and southwest. This study further chose the rice-growing zone of Punjab province as a specific focus of this research due to its agricultural significance and vulnerability to climate change (Khan et al., 2020d). The region produces over 60% of the country's total rice, an important food crop and an essential element of Pakistan's agricultural exports (IRRI, 2013; Khan et al., 2021a). Rice growing region is located in the irrigated plains[1] of Punjab province, consisting of over ten districts specializing in rice production (Ahmad et al., 2019). The region is globally famous for its aromatic rice varieties and is known as the *Kollar track*. However, during the last decade, the rice-growing zone has faced a substantial decline in rice yield, mainly due to climate change and its associated hazards. These climate hazards and risks include droughts of the late 1990s and early 2000s, extreme floods of 2010 and 2022, and depletion of water resources (Xie et al., 2013; MA and Mugera, 2016; Khan

1 Irrigated plains are one of three Agro-ecological zones (AEZs) of Punjab province.http://www.fao.org/3/ca6938en/CA6938EN.pdf.

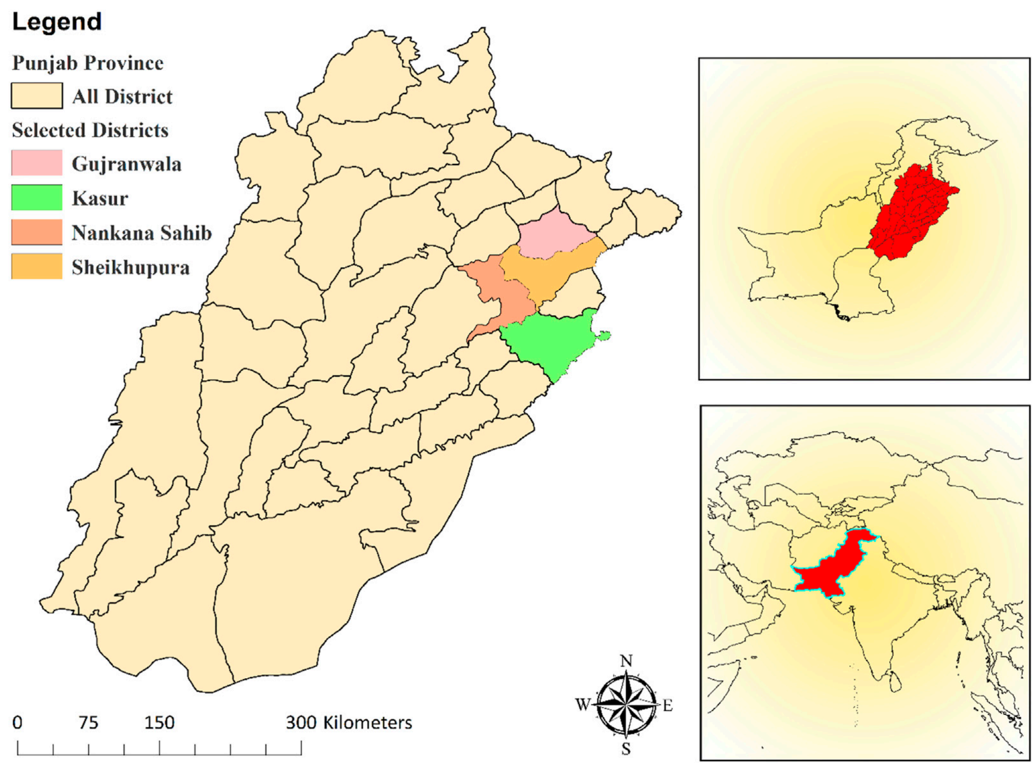


FIGURE 1
Pakistan in South Asia and Punjab on Pakistan's map (right), selected districts of Punjab (left).

et al., 2020a). The flood of 2010 affected eleven districts of Punjab, including the study area (PDMA, 2014). Such risks and uncertainties have made the cultivation of crops such as rice extremely susceptible. For instance, between 2009–2017, rice production declined by nearly 7% due to a 10% decline in land area under rice cultivation (AMIS, 2018). Studies show that the decline in rice production and cultivation area is mainly due to increasing average temperature, declining precipitation, and shrinking water resources of the region (Ahmad et al., 2015; Ali and Erenstein, 2017). Given these challenges, this research is conducted in the rice production zone of Punjab to investigate how farmers perceive changes in climate and what adaptation strategies they adopt. Specifically, four rice-growing districts are selected for this study, shown in Figure 1.

## 2.2 Sampling method and data collection

There are various methods of determining sample size available in the literature; this study, however, used the formula by Teddlie and Yu (2007), given the nature of the population. This approach is employed if the exact population of farmers is unspecified. In the current study, the exact population of rice farmers was unknown; thus, a sample size of 480 farmers was generated with an estimated proportion of the attribute in population $p = 0.5$, ±4.475% margin of error, and 95% confidence level, calculated as follows:

$$n_0 = \frac{Z^2 pq}{e^2} = \frac{(1.96)^2\ (0.5)\,(0.5)}{(0.04475)^2} = 480 \tag{1}$$

where: $n_0$ indicates sample size, the $Z$-value at 95% confidence level is 1.96, $e$ is the margin of error (4.475%), $p$ is the (estimated) proportion of the attribute in population $p = 0.5$, $q = 1\text{-}p$, hence $q = 0.5$.

This study considered a random-stratified, multistage sampling approach, where the sample was drawn in the following six steps. The reason for employing this sampling method is owing to the different hierarchical levels of the local population living in an area. Studies support the use of this approach if the population is distributed at different levels (Allen, 2017). Then the sample is determined by selecting farmers from each stage. The major benefits of this method include flexibility in determining the number of stages, sampling units, and methods at each stage, which make this approach more suitable for fulfilling survey requirements (Steel and Lovric, 2011). Therefore, following previous research (Shah et al., 2017; Khan et al., 2021c), we have chosen the farmers involving six stages. In the first step, using stratified sampling, the rice production region was divided into two groups, i.e., high production districts

TABLE 1 Sample distribution across the study area.

| Stage 1 | | Stage 2 | Stage 3 | Stage 4 | Stage 5 | Stage 6 |
|---|---|---|---|---|---|---|
| Production categories | Production range | Districts | Sub-districts | Union council | Villages | Farmers selected |
| High Production districts | 300–500 metric tonnes | Gujranwala | 2 | 4 | 8 | 120 |
| | | Sheikhupura | 2 | 4 | 8 | 120 |
| Low Production districts | 100–300 metric tonnes | Nankana Sahib | 2 | 4 | 8 | 120 |
| | | Kasur | 2 | 4 | 8 | 120 |
| Total | 2 | 4 | 8 | 16 | 32 | 480 |

Land unit in Pakistan (1 ha = 2.47 acre);<sup>2fn2</sup> PKR = Pakistani rupees (1USD = 163 PKR on 30 June 2019), source: (Field survey, 2019)

and low production districts, given each district's share of the total provincial rice yield. Our logic behind using the districts' total production instead of per hectare yield as the basis of categorization is because the per hectare yield is affected by several factors such as land productivity, input use efficiency, and technology adoption (irrigation, type of variety, etc.). Besides, in the study area, farmers grow different types of rice, such as long-duration rice and short-duration rice, which largely differ in terms of yield and market value; hence, considering per hectare yield could be misleading. Therefore, following Iqbal et al. (2016), who also adopted a similar sampling strategy, we considered the total production of the districts and categorized them into two groups, i.e., high production districts and low production districts, and selected two from each category. Table 1 shows the production range for categorizing the region. Following that, the second step involved the random selection of two districts from each yield group. Specifically, districts Gujranwala and Sheikhupura were selected from the high production zone, while districts Nankana and Kasur were selected from the low production zone. In step three, we randomly selected eight sub-districts (Tehsils) from both regions by choosing two from each district. In the fourth stage, using random sampling, we selected four union councils (UC, the second-smallest administrative unit of Pakistan's local government system) from each sub-district, making a total of sixteen UCs. In the fifth step, we randomly chose eight villages from one district (two from each UC), comprising a total of 32 villages. In the sixth and last step, we randomly chose fifteen farmers per village, making a total sample of 480 rice farmers. A list of farmers of the villages was obtained from the district agriculture department, and following that, farmers were randomly chosen from each village.

Data were collected using a predesigned structured questionnaire to obtain farmers' perceptions of and adaptation strategies to climate change. All the farmers were face-to-face interviewed, given their low literacy levels. The questionnaire was developed in the English language (see questionnaire in annexure); however, the questions were translated to the local language (Punjabi) during the interviews. A pre-test was also conducted on thirty farmers (outside the sample) to ensure the reliability and validity of the questionnaire. To facilitate the data collection process, two enumerators from a local university were hired and trained. The data collected was completed between June-August 2019.

## 2.3 Data analysis and empirical model

Farmers' perceptions of climate change were recorded using a Likert scale, where farmers were asked to indicate the changes in temperature and precipitation over the past 1–2 decades. Given that the average temperature in the country has increased by half a degree Celsius during the past 6 decades (Chaudhry et al., 2009), it is relevant to ask how farmers perceive temperature and precipitation changes at the local level. In this way, researchers intended to find whether farmers' perceptions are in line with the actual trends. The collected response was analyzed using simple percentages. Similarly, farmers' responses to adopted adaptation measures were recorded in the form of a binary variable, which takes a value of one if farmers adopt a certain adaptation measure and zero if they do not adopt that measure. While to determine the factors affecting farmers' adoption of various adaptation strategies, a regression analysis was conducted.

### 2.3.1 Binary logit model

This study chose a binary regression model given the binary nature of the dependent variables. Specifically, a binary logit model was employed to analyze the factors determining farmers' adaptation decisions, which is commonly used in similar studies (Kato et al., 2011; Bryan et al., 2013). This model gives relatively more precise estimates than similar models like the Linear Probability Model (LPM), which has certain limitations in heteroscedasticity and distribution abnormality of the error term (Iqbal et al., 2016). In this model, we assume that a farmer adopts an adaptation measure that has the maximum outcome in terms of reducing the adverse effects of changing climate (Kato et al., 2011).

Specifically, an assumed latent binary variable ($Y_{ij}$) equal to the expected outcome of adopted measures can be interpreted as:

TABLE 2 Descriptive statistics of explanatory variables.

| Variable name | Description | Mean |
|---|---|---|
| Farmers' age | Age in years | 47.25 |
| Farmers' education | Acquired schooling in years | 7.53 |
| Household size | Total family members | 6.58 |
| Primary occupation | 1 = farming, 0 = otherwise | 0.78 |
| Landholding | Total cultivated land in Acres[1] | 8.07 |
| Land ownership | 1 = farmer is the owner of the land, 0 = tenant | 0.88 |
| Tube well | 1 = farmer has irrigation borewell, 0 = No | 0.64 |
| Canal irrigated land | The percentage of land irrigated by canal water | 14.33 |
| Livestock units | Number of animals owned by HH | 4.59 |
| Farm labor | Continuous number of farm laborers | 1.98 |
| off-farm income | Continuous monthly income from non-farm sources, 000 PKR[2] | 11.05 |
| Access to farm advisory | 1 = farmer received, 0 = No | 0.42 |
| Access to credit services | 1 = farmer availed, 0 = No | 0.32 |
| Access to climate info | 1 = if farmer access, 0 = No | 0.61 |
| Farm location | 1 = farmer belongs to high yield zone, 0 = No | 0.50 |

$$Y_{ij} = \alpha + \sum X_k \beta_k + \varepsilon_{Y_{ij}} \quad (2)$$

where, subscript $i$ indicates a farmer whose crop is exposed to climate change, and subscript $j$ indicates response measures (adaptation strategies) that farmers adopt to avoid the potential risks. The symbols $a$ and $\beta$ indicate the intercept and coefficients of the binary regression model. $X_k$ refers to the vector of exogenous explanatory variables that influence farmers' selection of adaptation strategies, while the subscript $k$ indicates a particular explanatory variable (Table 2). $\varepsilon_{Y_{ij}}$ is an error term, homoscedastic and normally distributed, with constant variance and zero mean (Schmidheiny, 2013).

A binary variable cannot be observed directly; however, it is observed as:

$$Y^*_{ij} = \begin{cases} 0, & Y \le 0 \\ 1, & Y > 0 \end{cases} \quad (3)$$

where, $Y^*$ is an observed variable, indicating a farmer $i$ will only adopt certain measure $j$ if the expected benefit is more than zero (Y > 0), and will not adopt the adaptation measure if the expected benefit is below or equal to zero (Y ≤ 0). Eq. 3 can be reinterpreted in terms of an observed binary variable ($Y^*_{ij}$), where G refers to the specific binomial distribution (Eq. 4) (Fernihough, 2011).

$$Pr\left(Y^*_{ij} = 1\right) = Y^*_{ij} = G(\beta_k X_k) \quad (4)$$

### 2.3.2 Marginal effects

Parameter estimates of the logit model only give the direction of impact (βk) and the level of significance (p-value) of correlation between dependent and independent variables. However, they do not measure the magnitude of effects or the relationship between the dependent (adaptation) and independent variables (socio-economic explanatory). To do so, marginal effects ($Y^{*'}_{ij}$) were calculated to quantify the impact of per unit change in the explanatory variable (Xk) on the probability of unit change in the dependent variable Pr(Yij = 1) (Fernihough, 2011). The marginal effects equation for a binary logit model can be interpreted as follows:

$$\frac{\partial \mathrm{Y_i}}{\partial \mathrm{x_k}} = Pr(1 - Pr)\beta_{\mathrm{k}} \quad (5)$$

### 2.3.3 Evaluation of model fitness

Before estimating binary logistic regression, we checked the multicollinearity effect between the explanatory variables using the variance inflation factor (VIF) and did not find a high pairwise correlation among the selected variables. Further, to evaluate the *goodness of fit* of the developed models (seven models of farmers' adaptation measures), we adopted the commonly used null hypothesis approach. In this approach, all the models' coefficients ($\beta_k$) were assumed to be zero as null hypotheses, while alternative hypotheses with at least one value as non-zero.

$H_{1:}$ at least one $\beta_k \neq 0$

$H_0$: $\beta_k = 0$

Table 3 shows test statistics for model fitness. Pseudo R-square values ranged between 0.15 and 0.32, showing the model's strength in assessing determinants of adaptation decisions. Further, LR chi-square values for all logit models ranged between 17 and 99 and were significant at less than 1% probability level. Based on these indicators, we reject the null hypothesis and accept the alternative hypothesis (as at least one value of $\beta_k$ is non-zero). Hence it can be concluded that all the models fit significantly and can accurately estimate the

TABLE 3 Test statistics for model fitness.

| Models | -2 log likelihood | Prob > chi$^2$ | Pseudo $R^2$ | LR chi$^2$ (13) |
|---|---|---|---|---|
| Supplementary irrigation | −183.03 | 0.00 | 0.30 | 77.20 |
| Irrigation time changes | −184.97 | 0.00 | 0.28 | 23.12 |
| Short-duration rice | −220.69 | 0.00 | 0.15 | 12.97 |
| Climate-smart rice varieties | −165.75 | 0.00 | 0.22 | 92.31 |
| Cultivation date changes | −121.81 | 0.00 | 0.21 | 42.22 |
| Fertilizer management | −201.39 | 0.00 | 0.32 | 99.06 |
| Farm resize | −200.78 | 0.00 | 0.23 | 17.27 |

Prob > chi$^2$ indicates the significance level ($p< 0.01$) to accept the alternative hypothesis ($H_1$).

determinants of adaptation decisions (Peng et al., 2002; Stephenson et al., 2008).

### 2.3.4 Adaptation extent across different types of farmers: Three-way contingency table analysis

In addition to binary logistic regression, a three-way contingency table analysis was also used to understand the adaptation extent across the various regions and categories of the farmers. This method involved the division of variables into groups. For instance, in terms of adaptation extent, farmers were divided into four categories (from non-adaptation to high adaptation). A similar categorization was done for the selected explanatory variables. The contingency table analysis was done on three explanatory variables, i.e., farmers' education, access to climate information, and credit utilization status, to assess their adaptation extent across both study zones separately and in total. This is a descriptive analysis using cross-tabulation to complement the results of regression analysis.

A three-way contingency table analysis is a cross-classification of observed values *x_ijk, i = 1, . . . , I, j = 1, . . . ,J, k = 1, . . . , K of I×J×K* random variables, arranged in I rows, J columns, and K layers (Andersen, 1997). The interpretation of corresponding random variables could be as follows:

$$X_{111}, \cdots, X_{ijk} \sim M\left(n; \pi_{111,L}, \pi_{ijk}\right) \quad (6)$$

It is a multinomial distribution with number parameter $n$ and probability parameters $\pi_{ijk}$Where; $n = x\ldots = \sum_i \sum_i \sum_i xijk$

After conducting contingency table analysis, the results were presented as line graphs (Figures 4–6) to better understand and compare farmers' adaptation extent across socio-economic and regional attributes.

## 3 Results and discussion

### 3.1 Farmers' perception of climate change in the study area

Initially, farmers were assessed on their perception of climate change considering primary climate indicators, i.e., temperature and rainfall. Results (Figure 2) showed that farmers reported significant changes in the climate, which mainly included increased temperature and declined precipitation throughout the year. Specifically, results showed that over 80% of the farmers reported an increase in summer temperature in comparison to 60% who indicated an increase in winter temperature. Notably, 30% of farmers indicated a significant increase in the summer temperature. These findings show that temperature in general and summer temperature, in particular has increased according to farmers' perceptions. Similarly, regarding rainfall, results show overall rainfall has also decreased throughout the year. In particular, most farmers reported that rainfall has decreased during the summer and monsoon months compared to the previous 1–2 decades. Our findings are consistent with another study conducted in the southern part of Punjab province, where Hussain et al. (2020) reported that farmers perceived a rise in temperature; however, on the contrary, farmers in south Punjab reported an increased incidence of heavy rainfall. The perceived variation in rainfall could be due to the fact that both regions fall in different agroecological zones.

These findings suggest increasing vulnerability of rice crops as it is one of the crops facing significant yield decline due to temperature rise and shrinking precipitation. We further cross-checked farmers' perceptions with the actual temperature and precipitation trends in the study area, which revealed that the increase in mean annual temperature for north-eastern Punjab (the rice-growing districts) is mostly non-significant, while a significant temperature increase in mean temperature for winter is observed. Similarly, Syed et al. (2021) report that annual mean precipitation has not changed significantly; however, a significant change was observed in autumn. A study by Ahmad et al. (2015) states shrinking precipitation and rising temperature as the two major challenges to rice crops in Punjab province, projecting nearly a 35% decline in rice production by the end of this century if the temperature and precipitation variability continues. Such figures are alarming for the food security and livelihoods of the rural population as over one million farm households in the study

10.3389/fenvs.2022.997673

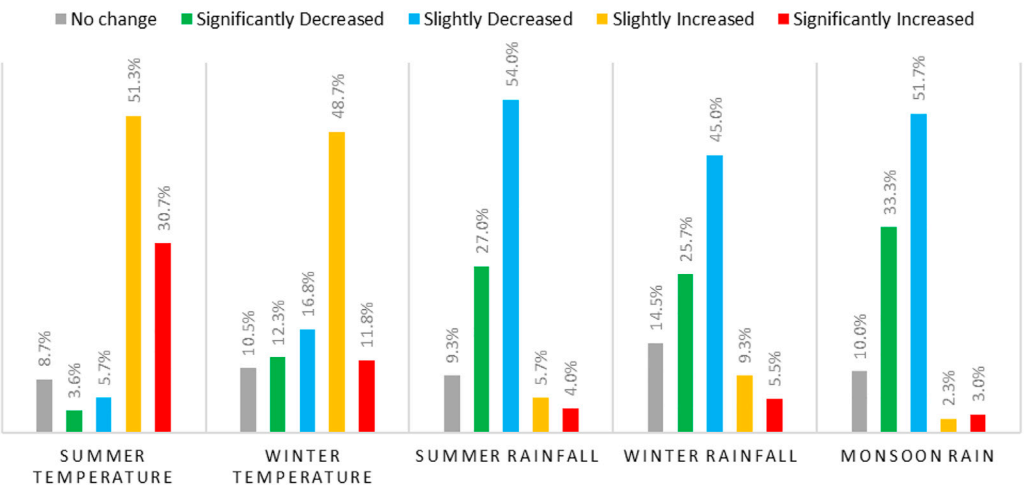


FIGURE 2
Perceived variability in temperature and rainfall.

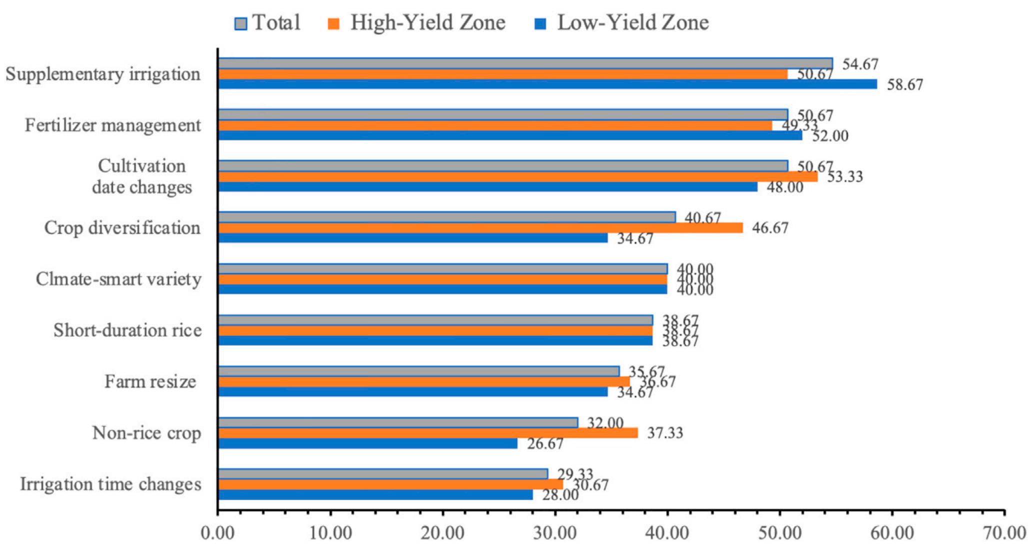


FIGURE 3
Farmers' adaptation strategies to cope with temperature and rainfall variability.

area depend on rice farming for their subsidence. It is, therefore, imperative to adapt rice farming to these changes in climate to avoid potential yield losses.

## 3.2 Farmers' adaptation strategies to climate change

Farmers in the study area were asked to indicate the respective adaptation measures which they adopt in their farming operations as a response to the changes in climate. During the interviews, the sampled farmers were requested to state only the strategies they adopted in response to their perceived impacts of climate change and variability. Findings (Figure 3) show that supplementary irrigation (55%), changes in rice cultivation dates (51%), and better fertilizer management (51%) were the major adaptation strategies adopted by the farmers. Further, farmers also reported use of crop diversification (41%), cultivation of climate-smart seeds (40%), cultivation of short-duration rice (39%), farm resizing practice (35%), shift to non-rice crops (32%), and altering irrigation time (29%) as key measures to cope with effects of changing climate.

These findings revealed that farmers implement a range of adaptation measures to adapt their rice farming to climate change in the study area.

### 3.2.1 Supplementary irrigation

Many studies show that the adaptation of agriculture to climate change is mainly the adaptation to water scarcity and shortage (Khanal et al., 2018a; Abid et al., 2020). Similar are the findings of this study as over half of the farmers considered the application of supplementary irrigation, making it the most adopted adaptation measure. This could be due to the rising irrigation requirement, mainly because of rising temperature, long and frequent droughts, and declining precipitation, which compel farmers to apply more irrigation to rice fields to mitigate temperature shocks. These findings are supported by a study in Bangladesh (Alauddin and Sarker, 2014), where rice farming communities apply additional irrigation to the rice field in order to avoid heat stress during extremely hot days. Similarly, in India (Dhanya and Ramachandran, 2016; Narayanan and Sahu, 2016), farmers also consider water application to the field when it is faced with the hot summer wind. However, in African countries (Thinda et al., 2020), the trend is slightly different as farmers' do not adopt supplementary irrigation as the most adopted strategy; rather, they mostly shift seed varieties. The possible difference between African and South Asian farmers' adaptation could be due to many factors, including different climate conditions and agroecological features. As temperature rise is more severe in south Asia than in Africa, farmers tend to rely more on additional irrigation.

### 3.2.2 Fertilizer management

Making crops physiologically healthy and resistant to environmental changes is another key measure adopted by farmers. This is done by using a good combination of fertilizers, which not only makes plants healthy and generates higher yields but also avoids the extra cost of non-required nutrients and fertilizers. According to Stuart et al. (2014), better management of fertilizers not only reduces climatic shocks and input costs but also enhances soil fertility. Half of the farmers in the study area adopted this measure, where some used a smart combination of fertilizers while some managed the plants' nutrients requirement by adjusting the supply of organic fertilizers obtained from the farmyard manure. Farmers reported that it is one of the good ways of improving plant health, given the negative impacts of climate change on plant growth. Our findings are similar to the study of Khanal and Wilson (2019), who also reported that Nepalese farmers use a proportionate combination of organic and chemical fertilizers to cope with climate change. These findings, however, contradict the case of Thailand (Arunrat et al., 2017), where farmers do not mostly rely on fertilizer management as an alternative strategy for climate change adaptation. The difference in the adoption of this strategy is mainly due to the variation of agroecological characteristics and farming culture of both countries, which are developed based on local knowledge.

### 3.2.3 Cultivation date changes

The change in crop cultivation dates is another strategy used by the rice farmers of Punjab. In this strategy, farmers shuffle the sowing and harvesting dates to avoid the expected occurrence of an unfavorable event. More than half of rice farmers adopted this strategy as a response to temperature and rainfall variability. This is mainly based on farmers' understanding of local climate patterns, where they may consider early sowing or transplanting if the temperature has risen before the usual time. This strategy also appears to be the most cited and commonly adopted measure among farmers in Africa and Asia (Cooper et al., 2008; Masud et al., 2017). However, the extent of reliance and adoption varies from region to region. For instance, in Malaysia (Masud et al., 2017), farmers rely more on crop planting and harvesting date adjustment compared with the case in Pakistan, where over half of the farmers were found altering rice cultivation dates in response to climate variability. In a South Asian country like Nepal (Khanal et al., 2018a; Khanal et al., 2018b), studies support these findings stating that rice farmers largely rely on crop operation adjustment in response to changes in cropping cycles and temperature and precipitation fluctuations.

### 3.2.4 Climate-smart varieties

Several farmers (40%) also adopted climate-smart varieties to cope with the changing climate. Change of crop varieties was done mainly in areas where previous varieties were highly vulnerable to temperature changes or could not give good yields. It was found that most farmers were looking mainly for those rice varieties which consume less irrigation water. However, no such varieties are available; rather, the farmers are provided with a few new varieties that are slightly heat-resistant and tolerant to climate shocks compared with the previous variety. Still, a considerable portion of the 60% of farmers cultivates old varieties because they are not familiar with the production technology and input requirement for new varieties. These findings are parallel with the study of Khanal and Wilson (2019), where a similar rate of new varieties' adoption is reported while contradicting the case of Nile Basin, Ethiopia, where farmers' adoption of improved seed variety is relatively higher. Mersha and van Laerhoven (2018) argue that the adoption of climate-smart variety is mainly led by institutions or planned adaptation where the local government contributes to the development and adoption of climate-smart technologies. However, in Pakistan, still, the planned adaption is at a nascent stage, and farmers are only open to very limited choices of seeds regarding a highly vulnerable crop like rice.

### 3.2.5 Cultivation of short-duration rice

Besides the adoption of climate-smart seeds, some farmers (32%) were found shifting to the cultivation of short-duration rice. Short-duration rice cultivation is a common practice in South Asian rice farming systems, where few varieties are harvested within 3 months of the cultivation cycle, compared to long-duration rice, taking over 4 months to be harvested. These findings are supported by the results of Alauddin and Sarker (2014), who also reported that most Bangladeshi rice farmers are shifting to short-duration rice, given the increased input cost needed for regular rice varieties.

This study considered the cultivation of short-duration rice as a separate adaptation measure because it is not a climate-smart variety (heat or drought-tolerant) but rather a risk-aversion response. Farmers relied on this strategy because they were not able to cultivate long-duration rice varieties like *BASMATI, SUPER,* and *SELLA* (local rice varieties in Pakistan) as they were unable to afford the cost of irrigation water and other inputs. The adoption of short-duration rice provides smallholder farmers with an alternative way to sustain their food and nutritional requirements by cultivating short-duration seeds such as *SUPRI, KAINAT* (rice varieties in Pakistan). However, the short-duration rice does not provide equal crop return as obtained through the long-duration rice because of the lower market value of short-duration rice. This is mainly because the long-duration rice has a special aroma[2], which is a distinctive feature of the rice of this region, while the short-duration rice is not that aromatic; hence people tend to prefer aromatic varieties more, which leads to a higher market value of the long-duration rice.

### 3.2.6 Crop diversification

Crop diversification refers to the cultivation of more than one crop species at the same time. It also means allocating some land area for another crop to diversify cropping systems to reduce the expected losses. Various studies alternatively use the term crop combination as well. Some scholars (Lim, 2018) argue that crop diversification is a livelihood adaptation rather than a farming adaptation because farmers reduce the land of a particular crop, affecting its production on a larger scale. We argue in support of the scholars that crop diversification is actually on the margins of farming adaptation and livelihoods adaptation, which shows both aversion[3] and response at the same time, as farmers respond with an alternative crop, but at the same, they reduce the crop's cultivation area which adversely affects production.

A considerable portion of the farmers was found shifting to other crops by reducing the cultivation area under rice crops. Specifically, 26% of the farmers were shifting to non-rice crops as they reported that rice is not a profitable business anymore in certain types of farms, making most farmers think about the alternative crops of the summer seasons such as pulses (moong, mash), maize, sugarcane, which relatively are less labor-intensive and input consuming. Farmers' diversification of crops and cultivation of non-rice crops could be the leading factors in declining rice cultivation area in Punjab province; for instance, provincial agricultural statistics show that from 2009–2018, the land area under rice cultivation has declined by 10%, causing a 7% reduction in rice yield (AMIS, 2018). These findings imply that farmers should be equipped with contemporary farming methods to sustain rice farming, as it is an important element of the country's agricultural exports.

### 3.2.7 Farm resizing

Farm resizing indicates a distinctive practice of rice farmers of Punjab province, which they usually adopt before the start of every rice cultivation season. This refers to the enlargement of rice plot size to over an acre[4], while usually, the plot sizes are one or half an acre for other crops. Farmers' expansion of plot size is coupled with land laser leveling, which makes a long plain plot for rice cultivation. In the study area, farmers irrigate their rice fields through a flooded irrigation method, where they have to spend long irrigation hours of electric or fuel-run tube wells. In this context, farmers' expansion of plot sizes is based on the notion that long smooth plots decrease the time and cost of irrigation. These findings are unlike the adaptation reported in other countries of Africa (ZY AmareAyoade et al., 2018), and Southeast Asia (Arunrat et al., 2017), where farmers do not make such changes in farm size. This could possibly be due to different irrigation methods practiced in different countries. In contrast, similar findings are reported in India, where land leveling for effective water harvesting is reported as a climate-smart measure (Khatri-Chhetri et al., 2017).

Over one-third of the farmers' adoption of such a strategy to cope with climate-induced water shortage indicate its usefulness, which implies the adoption of similar measures in other regions to cope with the climate-induced water-related issues in agriculture. Farmers largely advocated using this adaptation measure to reduce input costs spent on irrigation water.

### 3.2.8 Irrigation time changes

Change in irrigation application time to counter the heat waves and sun intensity was also found to be one of the adaptation measures of rice farmers. Over one-quarter of the sampled farmers indicated that they shuffle the times of irrigation application to avoid water loss. Farmers reported that they usually avoid irrigation at such time of the day when sun/heat intensity is high, which leads to higher evapotranspiration[5]. Hence irrigation application at certain times of the day (when evapotranspiration is minimum) reduces the irrigation costs. These indigenously developed adaptation measures may bring great benefits, particularly to those farmers

2 Aromatic rice of Pakistan https://www.cabi.org/GARA/FullTextPDF/2010/20103160491.pdf.

3 Risk aversion means changing farming decision under fear of risk. https://core.ac.uk/download/pdf/206245143.pdf.

4 Land unit in Pakistan, 1 ha = 2.4 acres.

5 A process when irrigation water evaporates from field to air.

who have fewer resources to adopt other adaptation measures, such as climate-smart varieties or supplementary water application.

## 3.3 Factors affecting the farmers' adaptation decisions

### 3.3.1 Farmers' age

The results of the binary logit model (Table 4) indicate that farmers' age has a significant positive effect ($p < 0.01$) on the probability of changing irrigation application time and cultivation dates while a significant negative effect on the adoption of climate-smart varieties. Marginal effects (Table 5) further show that a 1-year increase in farmer's age increases the likelihood of changing irrigation time and cultivation dates by 0.016% points and 0.001% points, respectively, while it decreases the likelihood of cultivation of climate-smart seeds by 0.005% points. The lower inclination of old farmers towards new crop cultivars could be due to their lack of knowledge or more reliance on conventional seed varieties, which led them not to cultivate new rice seeds. Similarly, more possibility of changing irrigation timing and cultivation times among the aged farmers could be due to their more farming experience and understanding of farming operations, which enable them to adopt these measures to avoid the negative effects of changing climate.

### 3.3.2 Household size

The size of a farm household, which represents the number of family members, is assumed to be an essential attribute associated with farm-related decisions. Our findings show that household size has a significant positive correlation ($p < 0.05$) with irrigation time changes, while there is a significant negative correlation between supplementary irrigation ($p < 0.01$) and crop variety ($p < 0.01$). The magnitude of the relationship further indicates that a one-member increase in household size decreases the likelihood of application of supplementary irrigation and changing crop variety by 0.048% points and 0.027% points, respectively, while it increases the likelihood of changing irrigation timing by 0.03% points. The negative relationship could be due to the farmer's lack of financial resources, which may limit their capacity to invest more money in buying new varieties and applying more irrigation. These findings are supported by Akhtar et al. (2018), who advocate that large farm households have fewer financial constraints as they have more human resources that improve their adaptive capacity. Likewise, the positive association with changing irrigation time could also be due to the availability of more family members to work as on-farm labor to make changes in irrigation application timings.

### 3.3.3 Primary occupation

It is further found that farmers who mainly rely on farming as their primary source of family income are more likely to apply supplementary irrigation, irrigation time changes, do better fertilizer management, and cultivate climate-smart varieties compared with those not relying entirely on farming. A strong relation among these strategies is because the farmers who have a greater dependence on farming are more concerned about climate risks and hence adopt major adaptation strategies. As they have relatively few or do not have an alternative source of income, hence adopt strategies to minimize the risks of climate change to their livelihoods. This proves that farmers take risks and apply new technologies to save themselves from climate change when their sole income source is their rice farm.

### 3.3.4 Landholding

Farm size, which indicates farmers' total cultivated land, showed a significant positive correlation with farm resizing ($p < 0.01$), better fertilizer management ($p < 0.1$), and climate-smart seeds cultivation ($p < 0.01$). In contrast, it has a significant negative relationship with irrigation time changes ($p < 0.01$) and the cultivation of short-duration rice ($p < 0.05$). This shows that big landlords adopted those measures that required higher input costs and resources such as farm machinery, income, and skills, given the fact the big farmers have more land assets. On the other hand, the lower likelihood of irrigation time changes and short-duration rice cultivation shows that farmers having large land assets are financially stable and are not concerned about resource-saving measures. Our results are similar to a study conducted in China (Zhai et al., 2018) reporting that peasants who cultivate larger land areas are more likely to adopt climate-smart measures than farmers with less farmland.

### 3.3.5 Land ownership

The negative coefficients of farm ownership status indicate its significant negative relationship with the farmers' application of supplementary irrigation ($p < 0.05$) and the cultivation of climate-smart seeds ($p < 0.1$). The values of marginal effects show that farmers who owned the farmland have respectively 0.14% points and 0.11% points less probability of applying supplementary irrigation and adopting climate-smart varieties compared to tenant farmers. The higher trend of adopting these measures tenants could be due to their more concerns about farm produce and crop return to meet the additional burden of the land fee. Fosu-Mensah et al. (2012) also argued that farmers' land ownership largely improves their adaptation intentions.

### 3.3.6 Tube well

Availability of tube well, which indicates farmers' access to an irrigation source, showed a significant positive correlation with supplementary irrigation application ($p < 0.01$), irrigation time changes ($p < 0.01$), and fertilizer management ($p < 0.05$). The marginal effects indicate that farmers having a personal tube well have, respectively, 0.16% points, 0.30% points, and 0.08% points more likelihood of applying supplementary irrigation, changing irrigation time, and managing fertilizer application. It is reported that water management measures are among the most effective adaptation strategies against climate change (Alauddin and Sarker, 2014); hence farmers' ownership of a personal irrigation source is a

TABLE 4 Parameter estimates of logit models.

| Explanatory variable | Supplementary irrigation | Change irrigation time | Short duration rice | Climate-smart variety | Change cultivation dates | Fertilizer management | Farm resize |
|---|---|---|---|---|---|---|---|
| Farmer's age | 0.0093 (0.0200) | 0.15921*** (0.0253) | −0.0119 (0.0161) | −0.0668*** (0.0231) | 0.0900*** (0.0205) | 0.0201 (0.0226) | −0.0185 (0.0169) |
| Farmer's education | 0.1065 (0.0788) | 0.0589 (0.0701) | −0.0040 (0.0601) | 0.0862 (0.0806) | 0.0291 (0.0702) | 0.1126 (0.0882) | −0.0201 (0.0649) |
| Household size | −0.4976*** (0.1418) | 0.3198** (0.1420) | 0.0687 (0.1233) | −0.3558** (0.1710) | 0.0162 (0.1264) | −0.1927 (0.1545) | −0.0886 (0.1374) |
| Primary occupation | 2.4313*** (0.6700) | 2.4020** (0.9388) | −0.7289 (0.4985) | 2.3912*** (0.7995) | 0.8142 (0.6151) | 1.5045** (0.6902) | −0.2443 (0.5729) |
| Landholding | 0.0411 (0.0357) | −0.1170*** (0.0442) | −0.0821** (0.0381) | 0.1602*** (0.0440) | −0.0550 (0.0357) | 0.0676* (0.0392) | 0.1196*** (0.0319) |
| Land ownership | −1.4999** (0.6644) | −1.1034 (0.7183) | −0.2245 (0.5342) | −1.4859* (0.8409) | 0.7139 (0.6463) | −0.2824 (0.7782) | 0.9105 (0.7352) |
| Tube well | 1.7587*** (0.4579) | 3.0284*** (0.6226) | −0.5502 (0.3479) | −0.4596 (0.5542) | 0.5537 (0.4032) | 1.0032** (0.5103) | 0.2986 (0.4603) |
| Canal irrigated land | 0.0401** (0.0158) | −0.0047 (0.0158) | 0.0077 (0.0127) | −0.0048 (0.0165) | 0.0156 (0.0145) | 0.0190 (0.0168) | −0.0199 (0.0142) |
| Livestock units | 0.2432* (0.1194) | 0.0241 (0.0923) | −0.3083*** (0.0958) | 0.1141 (0.0920) | −0.0854 (0.0643) | 0.2373** (0.1208) | 0.1949** (0.0901) |
| Farm labor | 0.1567 (0.2418) | 0.2723 (0.2328) | 0.3859** (0.1971) | −0.0902 (0.2934) | 0.4336** (0.2120) | 0.0753 (0.2607) | 0.3938* (0.2268) |
| Off-farm income | 0.0592** (0.0267) | −0.0629*** (0.0234) | −0.0092 (0.0217) | 0.0559* (0.0293) | 0.0043 (0.0221) | 0.1117*** (0.0308) | −0.0066 (0.0213) |
| Access to farm advisory | 1.9060*** (0.5786) | 2.4454*** (0.6154) | −0.8764 (0.4640) | 2.7622*** (0.5492) | 2.7973*** (0.4692) | 3.1887*** (0.6198) | 2.6097*** (0.4856) |
| Access to credit service | 1.4816** (0.6285) | 0.0377 (0.6162) | −1.2516** (0.5734) | 1.4925*** (0.5721) | 1.8337*** (0.6025) | 1.6042** (0.7153) | 0.5942 (0.5014) |
| Access to climate information | 0.3227 (0.4553) | −0.0480 (0.4642) | −1.0305*** (0.3508) | 1.4171** (0.6590) | 0.7087* (0.4140) | 0.6832 (0.4860) | −0.1701 (0.4929) |
| Farm location | 0.5278 0.4496 | 0.01967 (0.3996) | −0.1484 (0.3496) | 0.0526 (0.4837) | 0.1344 (0.3856) | 0.2782 (0.5085) | 0.3076 (0.3760) |
| Constant | −3.7745** (1.7114) | −15.1729*** (2.4336) | 3.0779** (1.3016) | −1.1961 (1.8402) | −8.7196*** (1.6713) | −7.1797*** (1.9848) | −3.7501** (1.4885) |

*, **, *** indicates significance level at $p < 0.1$, $p < 0.5$, and $p < 0.01$, respectively, and the values in parentheses are standard errors.


10.3389/fenvs.2022.997673

TABLE 5 Marginal effects of logit models.

| Explanatory variable | Supplementary irrigation | Change irrigation time | Short duration rice | Climate-smart variety | Change cultivation dates | Fertilizer management | Farm resize |
|---|---|---|---|---|---|---|---|
| Farmer's age | 0.0009 (0.0019) | 0.0160 (0.0017) | −0.0016 (0.0022) | −0.0051 (0.0017) | 0.0105 (0.0021) | 0.0015 (0.0018) | −0.0021 (0.0019) |
| Farmer's education | 0.0102 (0.0075) | 0.0059 (0.0070) | −0.0005 (0.0085) | 0.0066 (0.0062) | 0.0034 (0.0082) | 0.0089 (0.0069) | −0.0023 (0.0075) |
| Household size | −0.0480 (0.0125) | 0.0321 (0.0137) | 0.0097 (0.0174) | −0.0275 (0.0128) | 0.0019 (0.0148) | −0.0152 (0.0121) | −0.0102 (0.0158) |
| Primary occupation | 0.2345 (0.0591) | 0.2413 (0.0905) | −0.1033 (0.0695) | 0.1849 (0.0581) | 0.0955 (0.0716) | 0.1193 (0.0527) | −0.0283 (0.0661) |
| Landholding | 0.0039 (0.0034) | −0.0117 (0.0042) | −0.0116 (0.0052) | 0.0123 (0.0031) | −0.0064 (0.0041) | 0.0053 (0.0030) | 0.0138 (0.0033) |
| Land ownership | −0.1447 (0.0616) | −0.1108 (0.0710) | −0.0318 (0.0756) | −0.11490 (0.0645) | 0.0837 (0.0752) | −0.0223 (0.0616) | 0.1054 (0.0846) |
| Tube well | 0.1696 (0.0399) | 0.3042 (0.0509) | −0.0780 (0.0485) | -0.0355 (0.0425) | 0.0649 (0.0467) | 0.0795 (0.0400) | 0.0345 (0.0531) |
| Canal irrigated land | 0.0038 (0.0014) | −0.0004 (0.0015) | 0.0010 (0.0018) | −0.0003 (0.0012) | 0.0018 (0.0016) | 0.0015 (0.0013) | −0.0023 (0.0016) |
| Livestock units | 0.0234 (0.0112) | 0.0024 (0.0092) | −0.0437 (0.0126) | 0.0088 (0.0070) | −0.0100 (0.0074) | 0.0188 (0.0094) | 0.0225 (0.0102) |
| Farm labor | 0.0151 (0.0232) | 0.0273 (0.0231) | 0.0547 (0.0272) | −0.0069 (0.0226) | 0.0508 (0.0243) | 0.0059 (0.0206) | 0.0456 (0.0258) |
| Off-farm income | 0.0057 (0.0024) | −0.0063 (0.0022) | −0.0013 (0.0030) | 0.0043 (0.0022) | 0.0005 (0.0026) | 0.0088 (0.0022) | −0.0007 (0.0024) |
| Access to farm advisory | 0.1838 (0.0519) | 0.2457 (0.0545) | −0.1242 (0.0642) | 0.2135 (0.0334) | 0.3280 (0.0415) | 0.2528 (0.0384) | 0.3022 (0.0460) |
| Access to credit service | 0.1429 (0.0586) | 0.0037 (0.0619) | −0.1774 (0.0797) | 0.1154 (0.0417) | 0.2150 (0.0679) | 0.1272 (0.0557) | 0.0688 (0.0576) |
| Access to climate information | 0.0311 (0.0436) | −0.0048 (0.0466) | −0.1461 (0.0467) | 0.1095 (0.0500) | 0.0831 (0.0476) | 0.0541 (0.0379) | −0.0197 (0.0570) |
| Farm location | 0.0509 (0.0431) | 0.0020 (0.0401) | −0.0210 (0.0495) | 0.0041 (0.0374) | 0.0158 (0.0452) | 0.0221 (0.0403) | 0.0356 (0.0433) |

Average marginal effects (standard errors).

pivotal factor in determining their adaptation decision. More likelihood of shuffling irrigation application time basically shows that farmers have options in irrigation application times, i.e., they may water the field at a certain time when evapotranspiration rate, the process of evaporating water to air, is minimum. Moreover, fertilizer is usually applied during irrigation; hence personal tube well possession also enables farmers to better manage their fertilizer application. A study by Kelkar et al. (2008) also reported ownership of borewells to be a vital asset of Indian farmers to manage farm-level adaptation.

### 3.3.7 Canal irrigated land

In the study area, on average, farmers have had a 14% share of surface water (canal water) in meeting their irrigation needs. This secondary source of irrigation has a significant role in meeting farmers' irrigation needs, especially in the rice zone, which is facing severe water scarcity. Studies found that in Punjab province, the groundwater table has significantly depleted, increasing irrigation costs for many farmers (Bell et al., 2014). Our findings show that despite the trivial share in overall irrigation needs, canal water has a significant positive relationship with water management strategies. For instance, it appeared to have a significant positive effect on supplementary irrigation ($p < 0.05$). These findings revealed that farmers with improved availability of canal water are more likely to meet their irrigation needs which is the key determinant of higher rice yield.

### 3.3.8 Livestock

The size of the livestock herd (i.e., cattle, sheep, and goats) is considered farmers' important assets and income other than crop production. The results of our study also show a significant positive influence of farmers' livestock holdings on supplementary irrigation application ($p < 0.1$), better fertilizer management ($p < 0.05$), and farm resizing, with a magnitude of 0.02% points, 0.018% points, and 0.02% points, respectively. This indicates that farmers having large livestock herds are more likely to adapt to climate change. In the study area, people usually keep livestock as a reserved asset to generate additional income by selling milk and its products or save house expenditure by consuming them at home. Further, owning livestock also enables the farmer to make better use of fertilizers with an abundant supply of farmyard manure which improves soil quality and rice yield. Sertse et al. (2021) also report that livestock is an important asset for farmers in developing countries, which helps them cope with climate change.

### 3.3.9 Farm labor

This study further took farm labor, the number of available laborers for farm work, as an important factor to explore its correlation with farmers' adaptation decisions. We found a significant positive effect of farm labor on short-duration rice cultivation, cultivation date changes, and farm resizing. Specifically, the findings show that a one-laborer increase in farm labor increases the probability of short-duration rice cultivation, changing planting and harvesting dates, and farm resizing up to 0.05% points. This indicates that with the availability of laborers, households are more likely to shuffle rice cultivation operations and expand the sizes of the plots, which are mainly the labor-oriented adaptation strategies.

### 3.3.10 Off-farm income

We further considered farmers' non-farm income to see its relationship with adaptation strategies, as these income sources play a vital role in households' farming decisions. We found that farmers' non-farm income is significantly positively correlated with supplementary irrigation application, climate-smart seeds cultivation, and fertilizer management, while it is negatively significantly correlated with altering irrigation time. These results imply that farmers with more off-farm income are more intended to invest in supplementary irrigation in the form of separate groundwater irrigation or its conjunctive use with canal water. Further, the off-farm income also enables farmers to often change crop varieties and better manage fertilizer for improved yields and better resistance to changes in climate. These findings indicate that farmers with diverse livelihood options are more likely to adapt to changes in climate, possibly because they usually keep off-farm employment as precautionary savings to use in needy times. Further, the negative effect of more off-farm income on irrigation time changes shows that financial well-being which enables farmers to rely more on groundwater without being worried about the evapotranspiration of the field water. Another study (Akhtar et al., 2018) also found that farmers with more non-farming income have a positive attitude towards implementing new strategies compared to those who only rely on agriculture as their primary income source.

### 3.3.11 Access to farm advisory

Farm advisory services are the provision of farm management information by public or private sector extension agencies, and it has shown a significant positive impact on farmers' adaptation decisions. For example, results show that farmers' access to farm advisory improved their likelihood of changing irrigation timing, changing cultivation dates, fertilizer management, and farm resizing by 0.24% points, 0.32% points, 0.25% points, and 0.30% points, relatively. This shows that access to agricultural extension services not only improves farmers' understanding of local climate variabilities but facilitates them in adopting suitable measures to cope with changing climate effects by adjusting irrigation application time, transplantation and harvesting dates, better managing fertilizer, and expanding their plots. Various studies (ZY AmareAyoade et al., 2018; James et al., 2020; Kamruzzaman et al., 2022) have also found that agricultural extension is the key determinant of farmers' ability to adapt to climate change. This shows that farm advisory is an important factor in the decision-making process for rice farmers.

### 3.3.12 Access to credit services

This study further shows that farmers' credit access has a positive and significant correlation with supplementary irrigation application ($p < 0.05$), climate-smart varieties cultivation ($p < 0.01$), cultivation date changes ($p < 0.01$), and fertilizer management ($p < 0.05$), while a significant negative correlation with short-duration rice cultivation ($p < 0.05$). Marginal effects further show that farmers who accessed credit were 0.14% points more likely to apply supplementary irrigation, 0.11% points more likely to cultivate climate-smart rice varieties, 0.21% points more likely to shuffle cultivation dates, and 0.12% points more likely to do better fertilizer management. These findings basically show that access to financial capital improves farmers' adaptive capability and decision-making in choosing various adaptation measures. However, access to credit services reduced the likelihood of short-duration rice cultivation, inferring that the availability of finance enables farmers to consider regular or long-duration rice varieties, which generate higher income. Masud et al. (2017) have also indicated that Malaysian farmers having access to credit adapt their farming in a timely manner, which reduces the adverse effects of changing climate on farming. A study in Bangladesh (Sarker et al., 2013), however, contradicts our findings, stating that access to credit services increases the likelihood of short-duration rice cultivation. This variation could be due to the difference in the agroecological conditions of both countries.

### 3.3.13 Access to climate information

Information about potential climate events, i.e., unexpected rainfalls or temperature fluctuation, is among the key factors influencing farmers' adaptation intentions. We found a significant positive impact of such information's access on farmers' cultivation of climate-smart seeds and changes in rice cultivation dates. These findings show that information about weather forecasts increases farmers' adaptation likelihood, particularly in cultivating climate-smart seeds and shuffling cultivation time as per the potential weather changes. However, access to climate information is negatively associated with the adoption of short-duration rice. The lower probability of cultivating short-duration rice may be due to their informed decisions-led preparedness, which may lead to making savings or certain arrangements to afford the adaptation cost for long-duration rice cultivars. These findings imply that farmers' access to climate information, directly and indirectly, improves farm-level adaptation to climate change.

## 3.4 Adaptation extent across regional and socio-economic attributes

A contingency table analysis was used to understand the adaptation extent among different categories of farmers

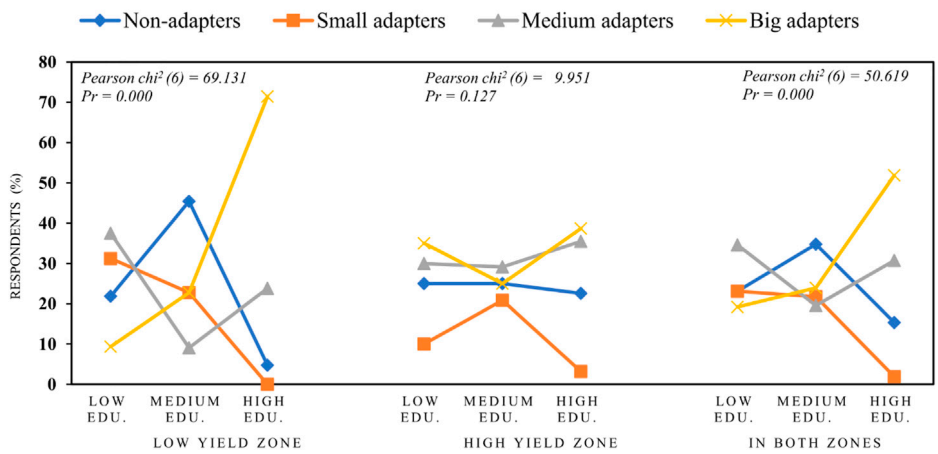


FIGURE 4
Climate change adaptation across farmers' education level.

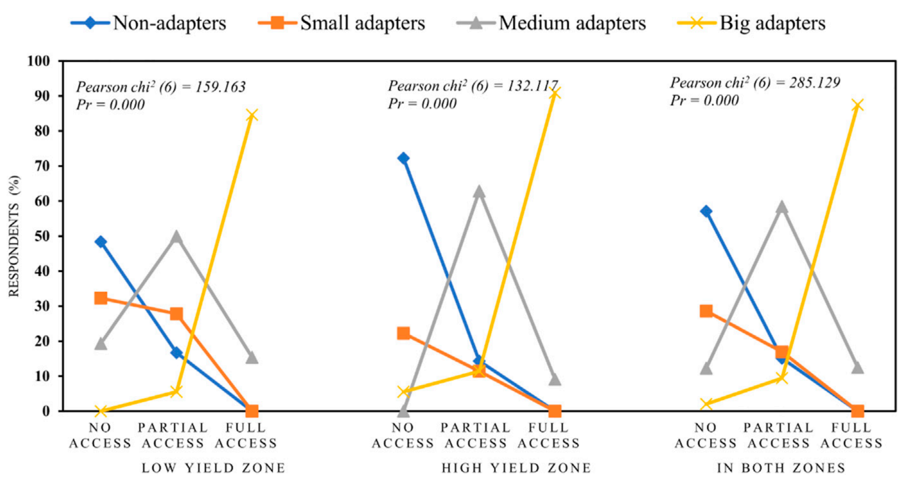


FIGURE 5
Climate change adaptation across climate information access.

based on socio-economic and regional attributes. Initially, farmers were categorized into four groups according to their adaptation level, i.e., non-adapters (no adaptation measure), small adapters (at least two measures), medium adapters (3–4 adaptation measures), and big adapters (over four adaption measures). Similarly, concerning socio-economic and institutional services, farmers were also categorized into different groups. For instance, in terms of education, there were three groups of farmers, i.e., low education (below 5 years of schooling), medium education (between 5 and 10 years of schooling), and high education (over 10 years of schooling) were made. A similar categorization was made based on farmers' access to climate information, i.e., no access, partial access[6], and full access[7]. The last category of farmers was regarding their credit utilization status, i.e., whether they had utilized credit or loans offered by public or private institutions.

6 Partial access means access to weather forecast only.

7 Access to forecast of weather and climate risks.

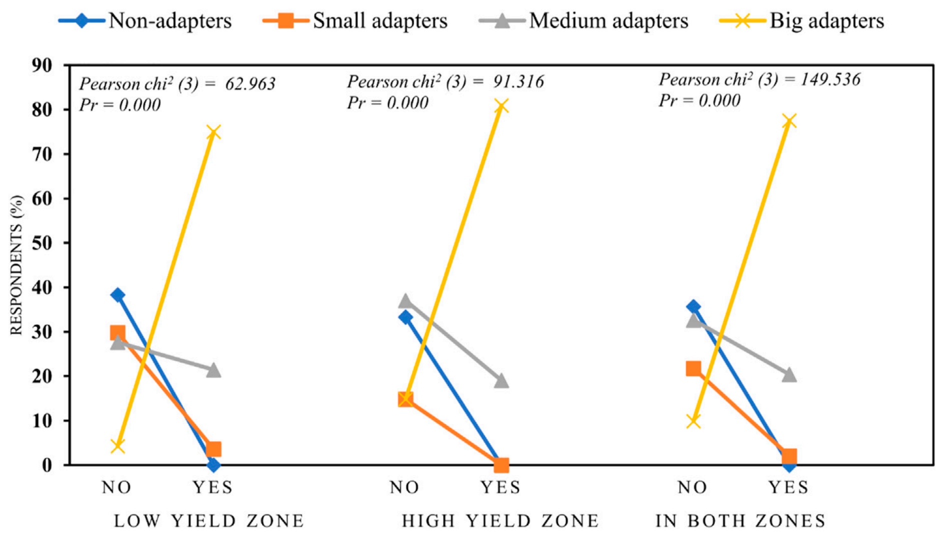


FIGURE 6
Climate change adaptation across farmers' credit access.

According to the results, the values of *Pearson chi-squared* and the significance level indicate a strong relationship with the adaptation extent and selected variables (Figures 4–6). This shows that the extent of adaptation significantly improves with increases in farmers' education levels and access to credit and climate information services**.** Specifically, in terms of education (Figure 4), the majority of the big adapters fall in the higher education category. In contrast, the non-adapters and medium adapters are comparatively less educated. Secondly, adaptation categories across farmers' climate information access (Figure 5) indicate that moving from no access to full access, the extent of adaptation also increases. For instance, in total, the majority of the big adapters have full access to climate information. In contrast, most small adapters and non-adapters have partial or no access to climate information services. This shows that access to climate and weather forecasts facilitates the farmers' adaptation extent due to farmers' better understanding of any changes that happen in local climate patterns.

Thirdly, in terms of credit services, results (Figure 6) show that, in total, most big adapters have utilized credit services, while the medium and small adapters did not indicate the utilization of credit services. Notably, none of the non-adapter farmers has utilized credit services, which infer that credit services increase the farmers' likelihood of adopting a large number of adaptation measures. This means farmers who utilize the credit services have a greater extent of adopting multiple adaptation measures. Studies show that adopting a diverse combination of adaptation measures helps to improve farmers' resilience compared to relying on single or very few measures (Teklewold et al., 2019). Hence farmers' access to these important institutional services has the potential to uplift the farming systems' resilience by increasing the extent of adaptation measures.

## 4 Conclusion and implications

Rice farming systems in Pakistan are highly vulnerable to climate change. This study aims to evaluate the farm-level perception of and adaptation strategies to climate change and its determinants in the rice-growing zone of Punjab province, a region highly vulnerable to climate change. A multistage sampling approach is used to select 480 farmers from the four rice-growing districts. Face-to-face structured interviews were conducted to collect data, and the collected data were analyzed using descriptive statistics and a logistics regression model.

The study found that farmers indicated significant changes in the local climate, reporting a significant increase in both summer and winter temperatures and a decline in precipitation. Farmers adopted various adaptation measures as a response to cope with the adverse effect of climate change on their rice crops. Among many, supplementary irrigation, better management of fertilizer, and adjustment in cultivation dates are appeared to be common adaptation strategies adopted by the farmers. Logistics regression analysis further showed that important attributes associated with farmers are the key determinants of the adoption of various adaptation strategies. Specifically, farmers' age, land size, access to irrigation water, credit service, farm advisory, and climate forecasts are major factors shaping their adaptation decisions. The study further found that adaptation extent (the number of adaptation measures) also improves with the increase in farmers' education levels and their access to important institutional services such as climate information and credit.

These findings conclude that these institutional services can play an important role in enhancing farmers' adaptive capacities and hence their resilience to climate change risks. Therefore, relevant institutions, concerned ministries, and policymakers are advised to improve farmers' access to these services. Specifically, credit and farm advisory services are the most critical determinants of both the adaptation decision and adaptation extent. Therefore, efforts should be made by agricultural banks to improve credit services provision on easy conditions, so farmers' adaptation levels could be enhanced. Similarly, the directorate of agriculture (extension) Punjab and other private advisory providers are recommended to provide farmers with climate-specific advisory so they could be well aware of the existing or potential variabilities in the climate and hence adapt their rice farming to it. Besides institutions, farmers should also make efforts to access relevant advisory services and implement them on their farms in order to cope with climate change.

This study has empirical, methodological, and policy contributions. Although climate change is a global phenomenon, the impacts of climate change are observed and realized at the local level. In this context, this study contributes to understanding how local people perceive changes in climatic conditions. Moreover, the study identifies location-specific adaptation strategies that can be further promoted. Furthermore, socio-economic factors affecting adaptations have been identified that are critical in implementing future adaptation actions. Thus, this research directly contributes to the United Nation's SDG13 (Climate action), which highlights the development of innovative solutions to adapt to climate change. Given the fact that Pakistan is a country that pays a huge toll due to climate change events, the findings of this study play an important role in designing and implementing robust climate change adaptation actions, programs, and policies in the agricultural sector. Rice is considered among the staple foods in Pakistan (and other south Asian countries) and is reported to be more vulnerable to climate risks compared to other food crops. The current study findings imply that farm-level adaptation can serve as a useful strategy to address the yield losses by positively impacting rice yield; hence, it can play a vital role in local food security. Finally, the methodology employed is relevant to many developing countries to identify location-specific adaptation strategies and determinants of adoption. This study does have limitations; it only deals with the farmers of the rice growing zone of Punjab province and cannot necessarily be generalized to other crops and regions of the country. Besides, this research only considered farm-level adaptation measures; thus, future studies should also investigate farmers' non-farm adaptation measures, i.e., livelihood adaptation strategies. Moreover, this research considered a small sample size compared to the on-ground farming activities; therefore, future research should consider a larger sample. Further, this research only focuses on farmers; therefore, future research should include office bearers of agricultural institutions to discuss the climate challenges faced by the local communities.

## Data availability statement

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

## Ethics statement

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. Written informed consent from the participants was not required to participate in this study in accordance with the national legislation and the institutional requirements.

## Author contributions

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

## Publisher's note

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# Appendix

TABLE A1 Rice production statistics for year 2018–2019.

| District name | 000 metric tonnes |
|---|---|
| Gujranwala | 470.04 |
| Sheikhupura | 376.80 |
| Hafizabad | 301.30 |
| Sialkot | 241.88 |
| Nankana Sahib | 239.27 |
| Kasur | 149.53 |
| Narowal | 130.96 |
| M.B. Din | 125.66 |
| Lahore | 71.47 |
| Gujrat | 54.39 |

Source (AMIS, 2018).

TABLE A2 Questionnaire used for the study.

| 1 | Question | Response |
|---|---|---|
| 2 | District | |
| 3 | City (Tehsil) | |
| 4 | Village ID | |
| 5 | Date of Survey | |
| 6 | Enumerator Name | |
| **SECTION B. SOCIO-ECONOMIC, LAND, AND RELATED CHARACTERISTICS** | | |
| 1 | What is your age | |
| 2 | What is your education? | |
| 3 | What is your primary occupation? 1) Farming 2) Employment 3) Own off business | |
| 4 | Experience in rice farming? | |
| 5 | Household size (numbers of family members) | |
| 6 | Landholding Size (acres) | |
| | 1) Owned 2) Share cropping 3) Tenant 4) Leased land 5) Owned + leased | |
| 7 | What kind of ownership does your household have on most of your land? | |
| 8 | Irrigation source 1) Electric tube well 2) Engine tube well 3) Canal 4) TW + Canal | |
| 9 | Do you own a tube well? | |
| 10 | Proportion of rice land that is irrigated by the canal water (%) | |
| 11 | Numbers of livestock that you have? | |
| 12 | What is your average monthly income in PKR | |
| 13 | Family members working as active labor on farm (numbers) | |
| 14 | How many family members are involved in non-farm job | |
| 15 | What is your average off-farm income/month | |
| 16 | Do you have access to farm advisory services? | |
| 17 | What type of organization is it? A. Government B. Non-government | |
| 18 | What is the frequency of contact with advisory services, particularly in rice cultivation season? | |
| 19 | Do you have access to the weather forecast | |
| 20 | Have you received credit during the rice cultivation (number) | |
| 21 | Are you an active member of any group/organization/farmers' cooperation/farmers' club? | |
| **SECTION C. PERCEPTIONS OF CLIMATE CHANGES** | | |
| 22 | Have you noticed/perceived any changing climate in your locality over last 10–20 years? | |
| 23 | Observed variation in summer temperatures (choose from the following) | |
| 24 | Observed variation in winter temperatures (choose from the following) | |
| 25 | Observed variation in summer rainfall | |
| 26 | Observed variation in winter rainfall | |
| 27 | Observed variation in rainfall during monsoon months | |
| 28 | Drought (Khushksali) | |
| 29 | Frequency of observed drought in numbers | |
| 30 | Floods | |
| 31 | Avail. of surface water | |
| 32 | Availability of groundwater | |
| 33 | Length of the Rabbi cropping season (winter) | |
| 34 | Length of the Kharif cropping season (summer) | |

1). Significantly decreased 2). Slightly decreased 3) No change 4). Slightly increased 5). Significantly increased

(Continued on following page)

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TABLE A2 (*Continued*) Questionnaire used for the study.

| SECTION D. CLIMATE CHANGE ADAPTATION | | | |
|---|---|---|---|
| 35 | Do you believe that adaptation minimizes the negative impacts of climate change in rice production | | |
| | **Adaptation strategy** | **Adopted** | **Constraints** |
| 36 | More irrigation | | |
| 37 | Cultivation short duration rice | | |
| 38 | Changed crop variety (climate-smart seeds) | | |
| 39 | Changed crop type (non-rice crop) | | |
| 40 | Changing planting and harvesting dates | | |
| 41 | Planting trees (Agro. forestry) | | |
| 42 | Fertilizer management | | |
| 43 | Changes in farm size (plots resizing) | | |
| 44 | Crop diversification | | |
| 45 | Changed irrigation application times | | |

Constraint 1 = Financial constraints, 2 = shortage of labor 3 = lack of information, 4 = expensive irrigation5 = Power cut (load shading) 6 = No access to the market service 7. Other (please specify).

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# A low-carbon and hunger-free future for Bangladesh: An ex-ante assessment of synergies and trade-offs in different transition pathways

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Feeding and nourishing a growing global population in Bangladesh is a major challenge in a changing climate. A multi-level participatory scenario approach with corresponding modeling and decision support tools is developed and applied to support decision-makers in developing scenario-guided enabling policy for food security in the future under climate change. The results presented in this paper show how, under different scenarios, the agri-food system may transform in the next decade as a result of the interaction of intertwined institutional, technological, and market drivers in Bangladesh. For scenario building, the food and agriculture community was brought together with the climate and energy community. We also experimented with different ways to bring voices that are often less included in policymaking, such as poor rural communities and youth. The scenario quantification is performed by MAGNET, a GTAP-based multi-sector and multi-region computable general equilibrium model. The simulation results depict a comprehensive picture of corresponding and varied pressures on agricultural resources and opportunities for economic development and trade in Bangladesh. Finally, we did an ex-ante assessment of the trade-offs and synergies between zero-hunger- and zero-emission-related targets within the Bangladesh Sustainable Development Goals (SDGs) under the developed scenarios.

KEYWORDS

**food system, CGE (computable general equilibrium), SDGs (6), scenario foresight analysis, climate challenge, evidence-informed decision-making, evidence-to-policy**

# 1 Introduction

Feeding and nourishing a growing global population is a major challenge, which will be further complicated by a changing climate (Yu et al., 2010; IPCC, 2021). Access to sufficient safe and nutritious food is far from universal. Inequality in the food system can be observed throughout, with unequal distribution of production and access to high-quality diets, leading to the so-called "triple burden of malnutrition" (Global Nutrition Report, 2020). At the same time, achieving the temperature target agreed upon in the Paris Agreement and the Sustainable Development Goal (SDG) 13 (Climate Action) will require substantial changes to societies everywhere. Food systems will play a new role in climate adaptation and mitigation efforts, as today, they account for between a fifth and more than a third of anthropogenic emissions (Rosenzweig et al., 2020; Crippa et al., 2021). Bringing together these key societal goals requires extensive changes, and depending on the chosen development pathways, there will be difficult trade-offs and potential co-benefits between the different objectives. Decision-making can often be highly technical and top-down, omitting sections of society, especially the poorest. Implementing change in food systems and for climate change mitigation is hampered by skewed power relationships and vested interests (Zurek et al., 2022). Food systems, which also provide the livelihood for the majority of the world's poor, are right at the intersection of hunger, poverty, environmental goals, and underpin resilient societies. Inevitably, there will be trade-offs between alternative pathways to achieving the zero-hunger (SDG 2) and zero-emissions (SDG 13) goals (Pradhan et al., 2017; Valin et al., 2021). These can be exacerbated if planning for one goal (e.g., zero hunger) without considering the implications of other goals (e.g., zero emissions). However, there will be opportunities for co-benefits if policies are designed based on various stakeholder perspectives and needs that span both goals. Therefore, the development of participatory scenarios or plausible futures can be helpful as this process can bring scientific and stakeholder communities together to guide such choices (Carlsson-Kanyamam et al., 2008; Henrichs et al., 2010; Kok et al., 2015; Vervoort and Gupta 2018).

Bangladesh is resource-poor and one of the most vulnerable countries to the impacts of climate change (Banerjee et al., 2015; Aryal et al., 2020a; Aryal et al., 2020b; Eckstein et al., 2020; University of Notre Dame, 2021; WMO, 2021). Inequality in the food system can be observed, with unequal distribution of production and access to high-quality diets (FAO-IFAD-UNICEF-WFP-WHO, 2018; Reggers, 2019). Across South Asia, the temperature has been increasing at a rate of 0.14°C–0.20°C per decade since the 1960s, coupled with a rising number of hot days and warm nights (IPCC, 2021). In this region, a likely increase in the annual mean temperature of 2.1°C–2.6°C is estimated to increase the heat-stressed area by 21% in 2050 (Tesfaye et al., 2017). Most projections of the general circulation models (GCMs) and the special report on emission scenarios (SRES) show that higher temperatures will lead to lower rice yields as a result of shorter growing periods (IPCC, 2021). This will contribute to greater fluctuations in crop production and food availability in Bangladesh. Moreover, food prices by 2050 are projected to be 2.5 times higher compared to 2000 for major food crops (e.g., rice, wheat, maize, and soybean) due to climate change (Nelson et al., 2009). In the absence of adaptation plans, rising market prices and economic losses from climate impacts will reduce the purchasing power of lower-income households, even in a fast-growing country such as Bangladesh (Wang et al., 2017). These impacts will be even more severe for smallholder farmers in Bangladesh because of poor infrastructure, limited access to global markets, low productivity, and lack of access to formal safety nets (Aryal et al., 2020a).

Although the agriculture sector is one of the most impacted by climate change, it is the leading contributor to Bangladesh's GHG emissions (WRI, 2022). The government of Bangladesh (GoB) has ratified many international agreements to reduce emissions and mainstream renewable energy sources. However, expediting economic growth, access to energy, and ending food insecurity and poverty have had to be prioritized. In the current nationally determined contributions (NDC), Bangladesh's mitigation contribution only covers the power, transport, and industry sectors, so the GoB is not using the many opportunities for reducing GHG emissions through mitigation and other low-carbon, climate-resilient development opportunities that exist for the agriculture sector. Furthermore, in Bangladesh, there exists a disconnect in the debate across the food security, poverty, and climate change communities due to various political-economic factors that play a significant role in policymaking and implementation (UNFCC, 2021).

Bangladesh has made substantial progress toward reducing hunger and improving the well-being of its growing population over the past several decades, as evidenced by its Global Hunger Index falling from 36.1 (alarming) to 25.8 (serious) (Grebmer et al., 2019) and halving of poverty rates. However, progress along these metrics has begun to slow in part due to increased flooding. Reflecting low incomes, rice continues to provide two-thirds of calories, with 15% of the population having insufficient access to calories, and insufficient dietary diversity continues to be a concern (Welthungerhilfe and Concern Worldwide, 2018). However, food and nutrition security is increasingly threatened by more frequent and severe extreme climate events. Supply shocks caused by the global pandemic and the war in Ukraine further show the high degree of fragility of the agri-food system with subsequent effects on food security. COVID-19 led to an unprecedented global breakdown of trade, transport, and face-to-face human interactions. Food systems were affected by disrupted supply chains, mobility restrictions, and loss of income. Although much remains uncertain, the economic contraction due to the global pandemic is projected to increase extreme poverty and the prevalence of undernutrition in developing countries such as Bangladesh by 20% (Laborde, Martin, and Vos, 2020) and 19%, respectively (FAO, IFAD UNICEF, WFP, and WHO, 2020). The pandemic has impacted food security in several ways. The main driver has been the loss of income and reduced purchasing power and access to food. The Bangladeshi garment sector, for example, which accounts for 80% of Bangladesh's export earnings (IFC, 2019), was severely disrupted by lockdown measures. Secondarily, food security has been impacted by mobility restrictions that have limited the functioning of food outlets, such as markets, further disrupting the supply of nutrient-rich but perishable foods (Laborde et al., 2020).

The most recent report on the "State of Food Security and Nutrition in the World" (FAO, IFAD UNICEF, WFP, and WHO, 2020) shows that raising the consumer price during the pandemic has made a healthy diet unaffordable for an additional 112 million people around the world. This estimate will be much higher if we account for the income loss during the pandemic and further the impact of the disruption in supply chains and the increase in fertilizers and energy prices due to the war in Ukraine. The pandemic mitigation measures hit the poor disproportionally, who relied more on physical labor, lacked options for remote work, and shifted food expenditure, comprising a large share of total expenditure, toward staples to meet caloric needs (Swinnen and McDermott 2020), potentially sacrificing long-run health.

This study was undertaken as part of the UK GCRF/Foreign, Commonwealth & Development Office (FCDO)-funded project "Zero Hunger-Zero Emissions" and aimed to support national and regional decision-makers in Bangladesh to develop scenario-guided policy and investment planning relevant to food security and climate change. Therefore, we analyzed together with stakeholders four scenarios on how food systems in Bangladesh may transform by 2050, based on different assumptions on changes to governance systems, as well as attitudes to dealing with climate and environmental change, and what these changes might mean for the food system and climate outcomes. To do this, we worked to develop and apply a participatory approach with corresponding modeling tools to create scenarios and analyze their implications. The study used the plausible futures/scenario approach to bring different stakeholder communities, which often do not talk together. Focusing on SDG 2 (zero hunger) and 13 (climate action), this brought the food and agriculture community together with the climate and energy community to discuss how to ensure food security in a world threatened by dangerous levels of climate change while at the same time making drastic cuts in greenhouse gas emissions. The project also experimented with different ways to make the process equitable and include perspectives that are often less heard in policymaking and technical debates, such as from poor rural communities or students and youth groups. The project was able to bring these different perspectives into a debate, thus testing the effectiveness of this technique. The project ensured dialogue on some contentious issues, such as the controversial debate on the need for low-carbon development from a developing country perspective and the role of food systems for this, especially as food security is the key political goal in Bangladesh. For this, the project developed four qualitative scenarios with stakeholders and quantified their implications by modeling a set of variables of interest, such as food security levels or GHG emissions from the agricultural sector up to 2050. The qualitative scenarios were also analyzed and presented to policymakers at the Planning Commission to integrate their views to identify and build consensus around the alternative pathways for achieving the zero-hunger/zero-emission goals by supporting the successful implementation of policies in a range of national contexts.

This paper presents the qualitative scenarios developed with stakeholders in Bangladesh and their quantification using the MAGNET model developed by Wageningen University. It discusses the methods used and the results of the quantification work with respect to achieving food security (SDG 2) and climate action goals (SDG 13) by 2050 and potential synergies and trade-offs of the different development pathways. In light of the economic impact of the COVID-19 pandemic being largely sector-specific and short-term in nature, we did not include the impact of the COVID-19 outbreak in our projections. MAGNET, like many other CGE models, is specifically parametrized to assess long-term impacts. The focus of the CGE models which have been used to assess the macro-economic consequences of the COVID-19 outbreak has so far been limited to the macro-level, with McKibben and Fernando (2020) estimating population and GDP effects and Maliszewska et al. (2020) assessing the impact on GDP and trade. In order to account for short-term disruptions in food security, there is a need for more research and new parameterization of the model, such as new estimation of elasticities of substitution in certain parts of the model to reflect the expected short-term nature of the pandemic.

The next section describes the data and methods used in this study. Section 3 describes the scenario narratives and their quantification, including the description of the four global contextual scenarios which are used to link Bangladesh-specific scenarios to the IPCC-based global Shared Socioeconomic Pathways (SSPs). Section 4 analyzes the results of the scenario quantifications and projections, focusing on the main outcome of each of the four pathways in terms of a set of sustainability indicators and analyzes the trade-off and synergies between SDG 2 and SDG 13. Section 5 presents a conclusion.

## 2 Data and methods

There are various methods for looking into the future. In this paper, we used a qualitative–quantitative scenario approach in developing a set of scenarios for the future of the Bangladeshi

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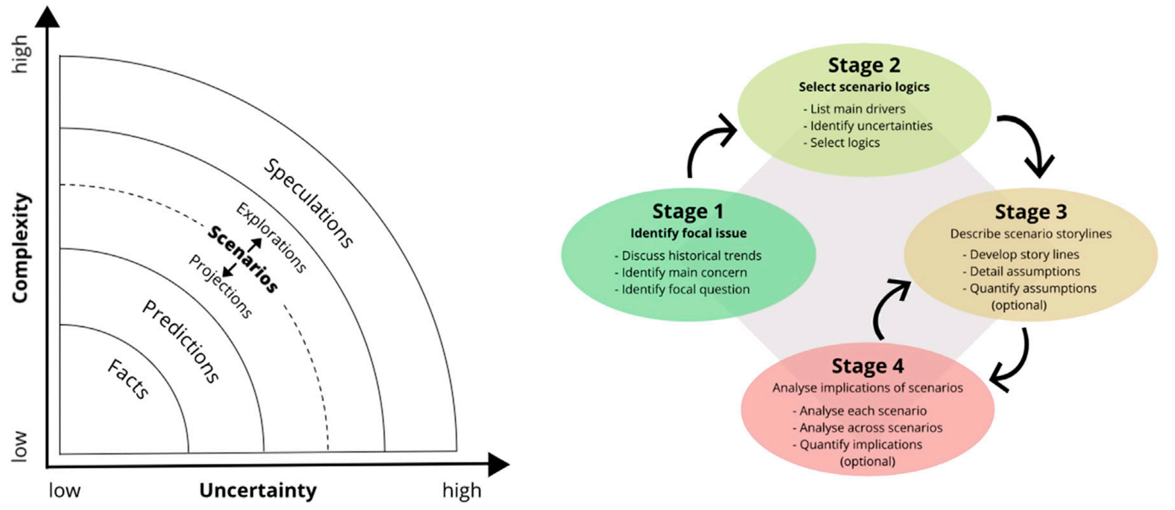


FIGURE 1
Describing how scenario work is framed in the study and which basic steps of the scenario development process were used.

food system and analyzed their implications. This section describes the basic methods we employed.

## 2.1 Development of qualitative scenarios for Bangladesh

For the development of scenarios, 20 Bangladeshi experts involved in the food or energy sector were interviewed in detail, followed by two workshops in which the participatory scenarios were built. The interviews revealed different perspectives on Bangladesh's future. However, food security was seen as the country's number one priority. A key finding was the lack of interaction between the existing agriculture and climate change/energy sectors in the country, which would have to work together in the future to address both the food security and climate change goals of the country.

In the two workshops with stakeholders from government and private sectors, academia, and NGOs, the project facilitated the development of four qualitative scenarios describing alternative future Bangladeshi food systems (for the specific methodology, see Henrichs et al., 2010). Figure 1 describes how the scenario work is framed in this study and the basic steps of the scenario development process. At the start of the scenario-building process, the participants were asked to identify the factors and issues driving change in Bangladesh and its food system. After the collation of the identified drivers, they were organized by category, and the participants were asked to vote for the main drivers of change in terms of their importance but also with respect to the uncertainty about their direction in the future. Thus, two drivers that were seen as both highly influential but also uncertain were identified: governance (inclusive or top-down) and the attitude toward dealing with environmental change (reactive or proactive). This led to four scenarios with different combinations of these drivers. The participants were split into four groups and asked to describe how Bangladesh and its food system might look like in 2041 with either inclusive or top-down governance and reactive or proactive environmental management. Different combinations of governance and environmental management options were identified: a Bangladesh with inclusive governance but bad/reactive environmental management; a country with proactive environmental management and top-down governance; a country with inclusive governance and proactive environmental management; and a Bangladesh with both top-down governance and reactive environmental management. After groups presented their depictions, they were tasked with determining the sequence of events from today that would lead to their imagined world to test the plausibility of the described end states of each scenario, thus developing a set of stories about how the future could unfold. This last step also included choosing two or three drivers from the list developed before and describing their status in the proposed future scenario to give more nuance and context to the developed scenarios. Thus, participants sketched out four plausible futures that might describe Bangladesh and its food system in 2041.

These scenarios were developed further over the following months and shared with rural communities, youth groups, and students for their reactions. The results of their deliberations were brought into the second workshop to help refine the scenarios. The final step of the qualitative scenario-building process was then a discussion of the implications of the different scenarios for various food security and climate change variables (e.g., in which scenario did people have higher levels of food security and in which scenario could the food system contribute more to a low-carbon future) and groups of society. Additional analysis variables included inequality, gender justice, and the potential trade-offs between food security and climate mitigation outcomes.

Looking across the different futures or scenarios allowed for a comparison of the implications of these futures for different groups in society and the environment, revealing important issues that decision-makers need to be aware of concerning future change. These deliberations were also shared in a third workshop with the Bangladeshi Planning Commission, which highlighted key challenges in the food system, including changing behavior, habits, and attitudes to food and how far people are willing—or able—to diversify to healthier diets, reduce consumption of highly sweetened foods, if possible, reduce the overuse of chemical inputs in agriculture, and reduce greenhouse gas emissions from the expanding beef and dairy sectors. Participants reflected that changing patterns in farming, such as male migration and the feminization of the rural workforce, presented challenges and opportunities for positive changes and "doing farming differently" and better *via* support for small-scale, often women, farmers with advice and credit, appropriate technologies, community enterprises, and co-operatives. Proper land-use planning and management are crucial too. For the energy sector, adopting new technology was identified as critical. However, it will need to be complemented by changing mindsets such that fossil-fuel-based energy models do not continue being the default option. Young people especially pressed for open discussion of ideas, wider engagement, and constructive questioning and urged stakeholders not to play blame games or delegate responsibilities.

The qualitative scenarios were then used to quantify input assumptions for the model.

### 2.1.1 The model

For the quantification of the pathways and scenarios, the agri-food tailored macro-economic model MAGNET (Woltjer et al., 2014) was used. The MAGNET model is a multi-regional, multi-sectoral, applied general equilibrium model based on neo-classical microeconomic theory (Nowicki et al., 2009, Woltjer et al., 2014; Van Meijl et al., 2018; Van Meijl et al., 2020a). The MAGNET database is built on the GTAP dataset (Aguiar et al., 2016). MAGNET assumes perfect competition, and producers are assumed to choose the cheapest combination of imperfectly substitutable labor, capital, land, natural resources, and intermediates. The core of MAGNET is an input–output (IO) model, which links industries in value-added chains from primary goods, over continuously higher stages of intermediate processing, with the final assembly of goods and services for consumption. MAGNET focuses on modeling agri-food markets and assumes that products traded internationally are differentiated by country of origin (Armington, 1969).

## 2.2 The model database and the improvement of household food expenditure data

The MAGNET database used in this study is an extension of the GTAP database V10, with 2014 as the reference year (Aguiar, Narayanan, and McDougall, 2016)[1]. In the construction of the GTAP database, not all data are available for each reference year, and therefore, an updating procedure suitable for generic application across all countries of the world is applied. However, data availability and data quality are always a concern in the construction of complex datasets for models. To this end, a previously developed updating procedure could be used to incorporate new information from our review of alternative Bangladeshi statistics. This is particularly relevant for Bangladesh, given that the input–output (IO) tables are relatively old, dating back to 1994, with the aforementioned GTAP generic updating of the tables to reflect changes in macro-trends in the 20 years between 1994 and the base year of MAGNET, which may miss structural and compositional changes in Bangladeshi expenditure patterns. This is because Bangladesh is not part of the production targeting procedure; the composition of private expenditures will only be affected by changes in trade, while it is confirmed that the total expenditure level is in line with the GDP of the GTAP year.

As the influence of changes in trade on consumption patterns is likely to be limited, the original IO expenditure structure will likely persist during updates of the GTAP dataset. This raises concerns given the 20-year gap between the most recent Bangladeshi IO data and the GTAP data used in MAGNET, which is particularly of concern due to the rapid increases in *per capita* income during this period, with GDP *per capita* (in constant 2010 US $) increasing by 84% from 433$ to 797$ or from 1.19 to 2.18 dollars per person a day. Given the solid evidence of Engel's law (Clements et al., 2017), changes in food expenditures beyond those captured by the GTAP database are expected.

To tackle the aforementioned issue, we used data from Waid et al. (2017), which describe changes in food expenditures for Bangladesh based on a consolidated set of nationally representative household surveys, which has been used in several studies for modeling the subnational level food security of Bangladesh (Waid et al., 2018; Hossain et al., 2019; Brown et al., 2021). All data in GTAP are expressed in dollar values and not physical quantities. These changes in value shares of key food groups over time give an insight into how we may need to adjust the MAGNET expenditure data. The data coverage is close to our 1994 IO reference year (1995) and 2011 GTAP reference year (2014). Although data from Waid et al. (2017) are presented in

**TABLE 1 Sources listed in column S refer to: 1 = SSP database (the datasets can be found here: https://tntcat.iiasa.ac.at/SspDb/dsd?Action=htmlpage&page=about# ; for an overview see Riahi et al, 2017 ); 2 = GTAP database (https://www.gtap.agecon.purdu).**

| Variables/ projections | Explanation | Spatial and temporal dimension | Source |
|---|---|---|---|
| **Drivers (exogenous variables in MAGNET model)** | | | |
| GDP growth | SSP database aims at the documentation of quantitative projections of the so-called Shared Socioeconomic Pathways (SSPs) and related Integrated Assessment scenarios (for an overview see Riahi et al, 2017). The GDP projections are based on harmonized assumptions for the interpretation of the SSP storylines in terms of the main drivers of economic growth. They differ however with respect to the employed methodology and outcomes. In case users can only use one interpretation of the SSPs, for each SSP a single 'illustrative' case has been selected. | →205 world regions<br>→2014-2050 | 1 |
| Population growth | For each SSP a single population and urbanization scenario, developed by the International Institute for Applied Systems Analysis (IIASA) and the National Center for Atmospheric Research (NCAR), is provided. | →205 world regions<br>→2014-2050 | 1 |
| **Model database** (calibration of MAGNET model for base year 2014) | | | |
| Input-Output (I-O) tables | Input-Output Tables (IOTs) includes the flows of final and intermediate goods and services defined according to product and industry outputs (product × product and industry × industry tables): | →Base year: 2014 | 2 |
| | →Intermediate and final uses of domestic goods | →57 economic sectors | |
| | →Intermdiate and final use of imports | →140 world regions | |
| | →Investment usage of domestic and imported products by commodity | | |
| | →Household and government consumption of domestic products and imports by commodity | | |
| | →Export by commodity | | |
| | →Change in stocks of domestic products and imports by commodity | | |
| International datasets of Macroeconomic aggregates | →GDP & GDP expenditure | →Base year: 2014 | 2 |
| | →Balanced bilateral trade of products & services | →57 economic sectors | |
| | →Energy data | →140 world regions | |
| | →Protection data such as import tariffs | | |
| | →Non-commodity indirect taxes, net, by industry | | |
| | →Employment of labour by industry | | |
| | →Employment of capital by industry | | |
| | →Employment of land by industry | | |
| | →Cmoddity taxes by commodity | | |
| | →Import duty by commodity | | |
| | → | | 3 |
| GHG Emissions | CO2, non-CO2 | →Base year: 2014 | |
| | | →57 economic sectors | |
| | | →140 world regions | |

(Continued on following page)

**TABLE 1 (*Continued*) Sources listed in column S refer to: 1 = SSP database (the datasets can be found here: https://tntcat.iiasa.ac.at/SspDb/dsd?Action=htmlpage&page=about# ; for an overview see Riahi et al, 2017 ); 2 = GTAP database (https://www.gtap.agecon.purdu).**

| Variables/ projections | Explanation | Spatial and temporal dimension | Source |
|---|---|---|---|
| Land supply | To implement the land supply function in MAGNET (Woltjer et al, 2011), data on agricultural land area per sector in each region are used | | 3,4 |
| **Updating MAGNET model database in line with Bangladesh Household surveys** | | | |
| Household food expenditure per food category | The datasets is constructed and consolidated based on the Household consumption and expenditures surveys (HIES) & Bangladesh Demographic and Health Survey (BDHS). It provides a common base to facilitate for research work with household consumption and expenditure data in Bangladesh while updating the average energy requirements for infants and young children for the WHO 2006 growth standards and 2007 growth reference curves. | As extensively described in the paper, we use the aggregated household food expenditure of this database to update the Bangladesh Social Accounting Matrix (SAM) which is constructed based on the GTAP data | 5 |

primary agricultural commodities, the underlying household survey data include composite dishes (or processed foods). These are converted to primary product content. Therefore, these data do not provide guidance on the developments in processed food.

Broad developments from 1995 to 2010 are in line with the cross-sectional patterns of food budget shares moving from low- to high-income groups (Clements et al., 2017): (1) decline in the budget of bread and cereals (starches); (2) increase in meat and seafood; and (3) small increase in dairy. However, the only evident difference is for fruits and vegetables, which increased slightly in Bangladesh (from 9.6% in 1985 to 11.0% of food expenditure), whereas the cross-sectional data show a declining expenditure share for higher-income groups. The budget share of fish in Bangladesh seems relatively high (12.3% in 1985, growing to 14.6% in 2010). Shares in the cross-sectional data for the lowest income quartile countries are 8.8% of food expenditures (these data refer to 2011). In contrast, meat expenditures grow from 5% to 8.8%, below the cross-sectional average for the lowest income quartile (13.2%). Thus, while the increasing trend in meat and fish expenditures is in line with the globally observed pattern, fish plays a more important role in the Bangladeshi diet compared to other countries at a comparable income level. Given the lack of

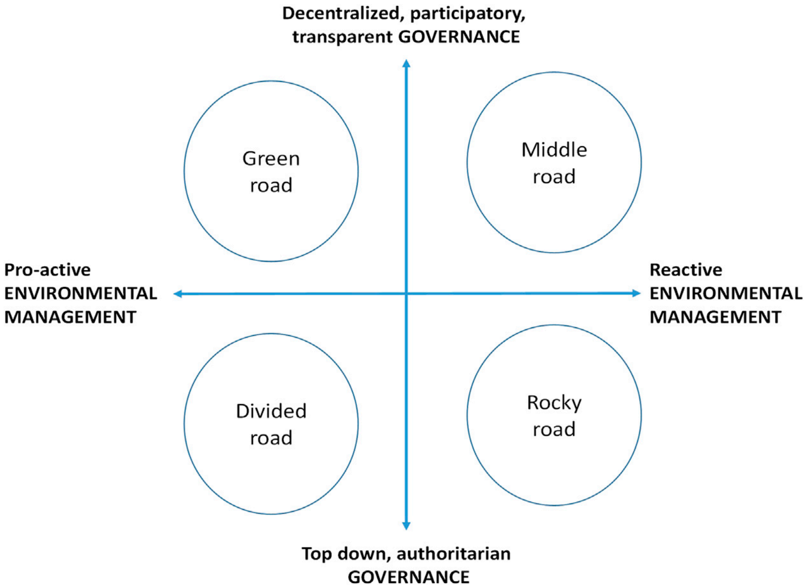


FIGURE 2
Scenario framework: either more decentralized, participatory, and transparent or more top-down and authoritarian.

information on processed and other foods in Waid et al. (2017) and at least rough alignment with the cross-sectional pattern in Clements et al. (2017), we used the latter as a reference when approximating changes in the MAGNET expenditure shares not covered by the household surveys. This is especially relevant from the perspective of food *versus* other non-food expenditures. Categories are also included in Clements et al. (2017).

Based on the previous analysis, we updated the base year data of the model using cross-entropy (CE), an approach based on information theory (Golan, 2007), which allows us to take varied sources of information (CGE model results, national accounts, socioeconomic projections, household survey data, and expert opinion), and reconcile them while minimizing the deviation from original datasets, and thereby allowing us to capture disaggregated household results, with respect to national totals and distribution of observed outcomes at the household level. This approach has been implemented in various settings to help reconcile economic datasets and assumptions for general and partial equilibrium models (Golan, Perloff, and Shen, 2001; Robinson, Cattaneo, and El-Said, 2001). It has also been used to disaggregate national accounts using household survey data in a process similar to our own initial micro-analysis (Robilliard and Robinson, 2003). The data sources and the main variable used for the scenario modeling and simulation are presented in Table 1.

# 3 The scenario narratives and simulation setup

## 3.1 Scenario narratives

As described in Section 2, the study developed scenarios in two workshops, using two scenario axes that describe four possible combinations or scenarios of the two main driving forces selected by workshop participants (see Figure 2). These combinations of the two drivers now constituted the basis for the so-called "scenario storylines." The two key drivers identified by the stakeholders were the type of environmental management that Bangladeshi decision-makers would adopt in the future (proactive *vs*. reactive mindsets) to address environmental problems and the type of governance system that would prevail in Bangladesh (decentralized, inclusive, and transparent *vs*. top-down and authoritarian).

### 3.1.1 The Divided Road

Bangladesh takes a Divided Road. A new government comes to power that promises to "clean up" society and the environment. Run by a strong man, it establishes a digitally controlled authoritarian system. Investment flows in from China as part of the Belt and Road initiative. Greater inequality is accepted. In some ways, the government is more effective; it creates a better economy and environment for some, but life is worse for many. The winners are the digitally savvy middle class, many of whom live in the high-tech new capital of Mymensingh. The majority of people, however, are deemed to be "anti-social" or "bad citizens." The government encourages agri-business and high-tech farming, which saves water and chemical inputs but needs little labor. Much food is grown for export to China. The environment is healthier for the better off, and there is a big boost in renewable energy. However, the promise to "clean up" environmental and social problems is a policy to "clean away" poor neighborhoods, so they are no longer so visible.

### 3.1.2 The Middle Road

In taking a Middle Road, historical trends continue. There are few radical departures from current policies and practices. Governance, inclusivity, and environmental focus and management are patchy. Despite good policies on paper, practice and implementation leave much to be desired. In theory, the Sustainable Development Goals unify policy. However, in practice, conventional economic growth takes priority. Despite a big expansion in solar power, the country is locked into coal. Coal power generation in the Sundarbans is a big factor explaining the collapse of the ecosystem there. The government strives to mitigate the impacts of disasters, but accelerating climate change is eroding the government's capacity to get ahead of the problems. Young people continue to drift to the cities, and farming becomes increasingly feminized.

### 3.1.3 The Green Road

Bangladesh treads a Green Road. Despite their quarrels, all political parties agree to have the Sustainable Development Goals as their guiding vision. Good governance, a more inclusive society, and a healthy environment are priorities. The government motto is "leave no one behind." "Digital Bangladesh" is a great enabler of good and effective governance. There are great efforts to boost agroecology and green energy and implement land reform and labor rights to boost health, education, and nutrition. As a climate leader, Bangladesh is a major recipient of money from the Green Climate Fund. However, there are still many problems. There is heavy pressure to continue to use artificial fertilizers and pesticides, agroecology runs up against land shortages, and creating a more inclusive government is slow and difficult and faces resistance. The legacy of environmental degradation proves hard to reverse in the short-term.

### 3.1.4 The Rocky Road

Climate breakdown, environmental decay, and political in-fighting set Bangladesh down a Rocky Road. Government is weak and erratic. Much of the economy is criminalized by being infiltrated by Yaba money. Parts of the country pretty much run themselves—some better than others. Whether a citizen lives well or badly depends on where they live, their connections with the powerful, and how rich they are, as they can buy services and

TABLE 2 Shared socio-economic pathway (SSP) scenario description, for more details, see Riahi et al. (2016).

| Scenario | Contextual global pathway | Description |
|---|---|---|
| Green Road | SSP1, Sustainability | A world that makes relatively good progress towards sustainability, with sustained efforts to achieve development goals, while reducing resource intensity and fossil fuel dependency. Elements that contribute to this are an open globalised economy, rapid development of low-income countries, a reduction of inequality (globally and within economies), rapid technology development, low population growth and a high level of awareness regarding environmental degradation. More environmental awareness reduces food waste, the appetite for meat as well as making land use regulation sector. |
| Mid Road | SSP2, Middle of the Road | A business as usual scenario. In this world, trends typical of recent decades continue, with some progress towards achieving development goals, reductions in resource and energy intensity at historical rates, and slowly decreasing fossil fuel dependency. |
| Rocky Road | SSP3, Regional Rivalry | A world which is separated into regions characterised by extreme poverty, pockets of moderate wealth and a bulk of countries that struggle to maintain living standards for a strongly growing population. Regional blocks of countries have re-emerged with little coordination between them. Countries focus on achieving energy and food security goals within their own region. The world has deglobalized, and international trade, including energy resource and agricultural markets, is severely restricted. Population growth in this scenario is high as a result of limited improvements in education and low economic growth. |
| Divided Road | SSP4, Inequality | A highly unequal world both within and across countries. A relatively small, rich global elite is responsible for much of the emissions, while a larger, poorer group contributes little to emissions and is vulnerable to impacts of climate change, in industrialised as well as in developing countries. Governance and globalisation are effective for and controlled by the elite, but are ineffective for most of the population. Land use regulation is strict in high/middle income countries whereas it is unsuccessful in low income regions. |

security. Belonging to a particular family or community can, in some parts of the country, buffer some of the difficulties, so the standard of living is quite varied across the country. Agricultural production falters, the industry cannot modernize, air and water pollution worsens, inequality increases, and severe hunger returns. As even more men migrate to survive, women are left behind to face the dual burdens of care and work. Farming is increasingly feminized, but women are vulnerable to violence from rascals trying to grab land.

## 3.2 Simulation setup

The scenarios were quantified using the agri-food tailored macro-economic model MAGNET (Woltjer et al., 2014). By using the socioeconomic assumptions from the scenario narratives, all the scenarios were ranked with respect to a baseline. These rankings were taken as inputs for the MAGNET model. The model was able to provide us with a range of different output variables which we could choose from. In the development of the quantified scenarios, we identified two levels of influence: the level of global socioeconomic development (contextual scenarios) and the level of the four scenarios for Bangladesh, which were developed in this study and outlined in detail in the previous section.

The contextual baseline scenario is constructed based on several assumptions, as set out in the following. It is assumed that the baseline follows a middle-of-the-road shared socioeconomic pathway (SSP2) up to 2050, meaning that the world economy as a whole is expected to face moderate social and economic challenges over the coming decades, as suggested by the assumed GDP and population growth rates. The narratives of the SSP scenarios can be found in detail in O'Neill et al. (2016). Table 2 summarizes the SSP scenario narratives and assumptions.

The scenario is implemented in MAGNET and quantified. Table 3 shows the main scenario-specific characteristics for macro-economic development and specific land-use components (for more details, see Doelman et al., 2017).

# 4 Results

## 4.1 Drivers

On the basis of the aforementioned scenarios and how Bangladesh may develop in the global context in the long-term, the following key contextual scenario projections are inferred from the SSP scenarios linked to the Bangladesh-specific scenario.

### 4.1.1 Population and GDP

In SSP scenario narratives, population and economic developments strongly impact the ability of societies to anticipate mitigation and adaptation challenges. For example, a larger, poorer population will face more difficulties adapting to the effects of climate change. In SSP2, the global population will grow to 9.4 billion people by 2070 and slowly decline thereafter (KC and Lutz, 2015). GDP follows regional historical trends and grows by a factor of 6 in SSP2 by the end of the century, with the global GDP/capita reaching about 60 (thousand year-2005 USD/capita, purchasing-power-parity—PPP) (Dellink et al., 2015). The SSP2 income projection is situated in between the

**TABLE 3 Scenario-specific characteristics for macro-economic development in agri-food sector and specific land-use components (for more details, see Doelman et al. 2017). Notation: LIC: 'Low Income Country'; HIC: 'High Income Country'.**

| *Scenario* | Green Road | Mid Road | Rocky Road | Divided Road |
|---|---|---|---|---|
| *GDP growth* | High in LICs, MICs; medium in HIC | Medium, uneven | Slow | Low in LICs, medium in other countries |
| *Population growth* | Low | Medium | High | Medium |
| *Inequality* | Reduced across and within countries | Uneven moderate reductions across countries | High, especially within countries | High especially across countries |
| *Land use change regulation* | High | Medium | Low | From strong in HICs to low in LICs |
| *Agricultural productivity* | High | Medium | Low | High in HICs and low in LICs |
| *Trends in meat preference* | Negative preference shift for meat | Endogenous meat consumption dynamics | Positive preference shift for meat | Endogenous meat consumption dynamics |
| *Food waste* | Reduced food waste (one third lower than SSP2) | Current level of food waste (33% of production) | Higher level of food waste (one third higher than SSP2) | Current level food waste, as SSP2 |
| *Trends in agricultural commodities* | Abolishment of import tariffs and export subsidies | Current import tariffs and export subsidies | 10% import tax for agricultural products by 2050, for self-sufficiency concerns. | Abolishment of import tariffs and export subsidies and increase export cost of food from LIC to HIC. |

estimates for SSP1 and SSP3, which reach global average income levels of 82 and 22 (thousand year-2005 USD/capita PPP) by 2100.

For Bangladesh, the assumed population growth trajectory in all four scenarios is presented in Figure 3. In all four scenarios, the population in Bangladesh is expected to increase. In Rocky Road (SSP3), Bangladesh is expected to have a much larger population in 2050 compared to other scenarios. In Rocky Road and Middle Road, Bangladesh assumes a consistent increase in population, with the fastest growth projected during the 2030–2050 period. In contrast, the Green and Divided Roads show a slowdown in population during this time period. In the case of Green Road, this slowdown is in line with a general expectation that population growth would ease as economic growth picks up, as shown in Figure 4. This clearly should be understood in a relative sense.

As shown in Figure 4, the assumed GDP growth rates across all four scenarios are expected to increase in the period 2011–2050, although the growth trajectory varies across the four scenarios and over time, where Bangladesh is expected to see faster GDP growth during 2030–2040 followed by a gradual slowdown. This is in contrast with the Divide Road, in which Bangladesh will be experiencing a gradual slowdown in GDP growth throughout the two projected decades.

### 4.1.2 Land productivity

Changes in land productivity in the model comprise exogenous and endogenous components. Endogenous changes in land productivity are primarily driven by changing prices in the model, as these would cause the reallocation of economic resources and reshuffling of land-based activities, resulting in changes in land productivity. Exogenous factors reflect assumptions on overall technical progress (e.g., fertilizer application and irrigation) and improvements in land management. Exogenous changes in land productivity are expected to be overall positive in all the scenarios. Land productivity in Bangladesh, in general, shows a slowing growth over the projection periods based on estimates from the IMAGE model (Stehfest et al., 2014). In general, the changes in the ratio are negative in all the regions, reflective of contractive trends in agricultural land supply over the long-term.

### 4.1.3 Labor, capital, and natural resources

Supplies of labor, capital, and natural resources in Bangladesh are exogenously given in the model. The supply of labor, including skilled and unskilled labor, is assumed to follow population growth trajectories, whereas the supply of capital is assumed to follow the growth of GDP. Moreover, the supply of natural resources is assumed to take a quarter of the underlying GDP growth rates. Thus, assumptions on the supply of these primary factors are consistent with the assumed GDP and population growth, indicative of similar regional and dynamic patterns, applicable to the supply of these endowment commodities.

## 4.2 Sustainability impact

### 4.2.1 Agri-food production, consumption, prices, and trade

One of the important aspects under the model's coverage is the agri-food system, which is also essential in analyzing food security in this paper. The model projects, among other things, agricultural and food production, consumption, and prices for individual commodities and sectors in Bangladesh. Figure 5 presents the projected changes in total production, private consumption, and real market price in the agri-food sector in Bangladesh across all four scenarios.

Agri-food production and consumption in Bangladesh are projected to increase in all the scenarios. The weakest growth is in Rocky Road. As shown in the previous section, the Bangladeshi population in all four scenarios is expected to grow between 2014 and 2050. At the same time, *per capita* incomes in 2050 are projected to be a multiple of the base year's levels. These trends mean that market demand for food will continue to grow, suggesting significant increases in the production of several key commodities. While largely driven by domestic consumption, agri-food production in Bangladesh also needs to compete with imports from other regions, which is projected to emerge in scenarios where economic growth is expected to be high, especially Green Road in 2011–2040. The total import value increased in 2014–2050 due to the 50% reduction in the trade tariffs with all other regions assumed in this scenario (see Table 4).

The full agricultural trade liberalization between Bangladesh, South-East Asia (SEA), and China, which is assumed in the Divided Road in 2030–2050, results in slightly positive growth in the net export value for Bangladesh compared to the other scenarios (Figure 6).

### 4.2.2 Food security

To account for the various aspects of food security, we follow the FAO's distinction of availability, access, utilization, and stability. We derive model-based indicators for the first three dimensions: food availability, food access, and food utilization. These indicators have been developed and elaborated for the FOODSECURE and IPCC scenarios (van Meijl et al., 2020, respectively). We measure food availability in kcal *per capita* per day (food available for consumption, e.g., Nelson et al., 2014; Von Lampe et al., 2014). This includes all domestically produced and imported food available for consumption at the household level.

Food access relates to people's food purchasing power (FPP) and, therefore, to food prices, dietary patterns, and income development (Lele et al., 2016). A first and crude proxy for food access is the change in agri-food prices. The income dimension of food access is neglected in this often-used indicator. The "food purchasing power" (FPP) indicator considers the income dimension by relating the price development of a specific food consumption basket to the income development of a particular income group. More specifically,

$$\Delta FPP = \frac{\Delta\, Income}{\Delta Price}.$$

In line with Van Meijl et al. (2020a), we use the consumption of cereals (rice and grains) for the food basket as a proxy for the diet of people potentially in poverty, as rice is an important food component of low-income groups in Asia, whereas grains are important in Africa. For the income component of low-income groups, the wages of unskilled (production) workers in the cereals sector are used as a proxy. Less sophisticated proxies are used for the food utilization dimension.

The fraction of calories derived from fruits and vegetables in total calories of food consumption is used as a proxy for food utilization, following the FAO compendium of indicators for nutrition-sensitive agriculture (FAO, IFAD, UNICEF, WFP-WHO, 2018; Van Meijl et al., 2020).

#### 4.2.2.1 Food availability

Overall, the food availability in terms of kcal *per capita* per day is increasing in all scenarios (Figure 7) due to higher GDP growth and an overall increase in agricultural production. This indicator shows a relatively higher growth in the Green Road as food availability increases owing to the increase in imports of agri-food products, lower prices, and a relatively higher GDP *per capita*. The other scenarios show relatively less improvement in food availability compared to the Green Road. The Rocky Road has the lowest growth in food availability and even slightly negative growth in 2040–2050 due to a lower GDP/capita growth, an increase in food prices, and a decrease in the food supply, both domestically produced and imported in this period.

#### 4.2.2.2 Food accessibility

The indicator for food access is the food purchasing power of cereals for unskilled agricultural workers (Figure 8). Unskilled workers in the cereal sector are used as a proxy for unskilled agricultural workers. For the food basket, we use the consumption of cereals (rice and grains) as a proxy for the diet of people potentially in poverty. We use changes in the wages of unskilled workers in the cereals sector as a proxy for the income component of poor people.

Overall, this indicator shows a relative improvement in all the scenarios due to the overall increase in income *per capita*. In the Rocky Road, the indicator declines in 2030–2050 caused by lower income/capita growth. Despite higher agri-food prices (cereals), the wages for unskilled people (cereal sector) decrease due to lower economic growth.

#### 4.2.2.3 Food utilization

According to Ruel (2003), micronutrient deficiencies and the burden of non-communicable diseases can be reduced by dietary changes. In this paper, we use the share of calories derived from fruits and vegetables as an imperfect proxy for food utilization (Figure 9). This share rises for an average household in Bangladesh in all the scenarios due to the higher availability and accessibility to a diverse food basket. Despite a high level of access and availability in the Green Road, we do not see a proportional improvement in the utilization. The indicator even shows a decreasing growth rate in 2030–2050. These

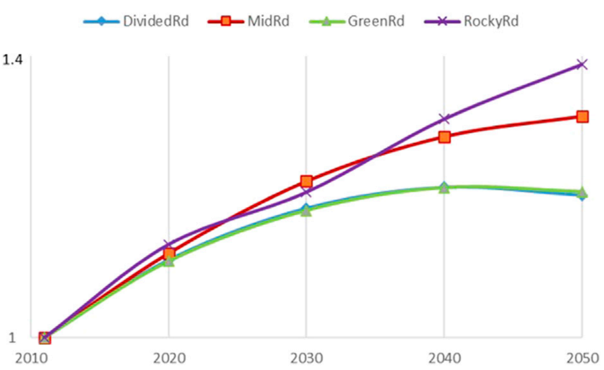


FIGURE 3
Population growth index in algorithmic scale (2011 = 1).

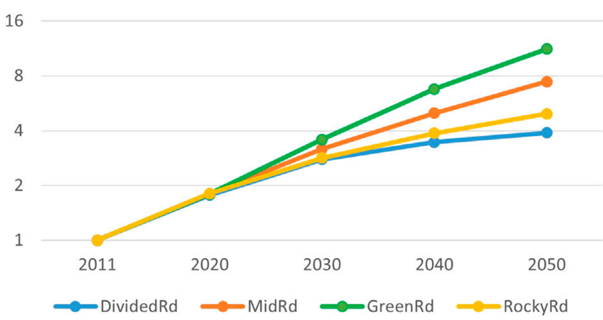


FIGURE 4
GDP PPP growth index in algorithmic scale (2011 = 1).

results are in line with the anticipation that a shift toward fast food will likely shift diets to incorporate fewer whole foods (fruits and vegetables) and more processed foods, especially as we do not assume any exogenous dietary shifts in the scenarios.

### 4.2.3 Environmental impact

MAGNET accounts for different emitting gases ($CO_2$, $N_2O$, $CH_4$, and F-GASes) and different source fuels and activities (coal, crude oil, gas, petrol, chemicals, fertilizer, and industrial activities) as a part of its greenhouse gas emission projections, with aggregate projections across all gases and sources reported in Figure 10 for the agri-food sector.

GHG emissions are projected to increase in all scenarios, in line with the assumed economic expansion in these scenarios. Growth in emissions in the two fast-growing scenarios (Green Road and Middle Road) is expected to be substantially higher than in the other regions. However, in the Green Road scenario, Bangladesh complies with the 10% emission reduction target for all sectors, which results in lower growth compared to Mid Road, in which Bangladesh meets the 5% reduction in GHG emission with no mitigation measure taken in the agriculture sector. Despite more drastic mitigation measures and much higher $CO_2$ efficiency in the Green Road (Figure 10), the total GHG emission level is projected to be 70% higher compared to the base year.

Furthermore, the Green Road results in the highest agricultural land pressure compared to the other scenarios (see Figure 11), especially in 2030–2050, in which Bangladesh enjoys very high economic growth.

## 4.3 SDG indicators: Synergies and trade-offs

In this section, we present some SDG indicators derived from the SDG insight modules in the model. These indicators complement the variables reported previously, facilitating measuring progress toward the SDGs. Although the SDG modules produce individual indicators consistent with the broad SDG framework, we summarize these indicators using a widely recognized framework known as "People, Planet, and Prosperity." One advantage of this framework is that it allows us to scrutinize a wide range of SDG indicators through succinct yet inclusive lenses covering social, economic, and environmental domains.

### 4.3.1 People

Several people-related indicators derived from the SDG 1 and SDG 2 modules are reported in Figure 12. These indicators, including the ratio of rural wage (for unskilled workers) to cereal price, calorie consumption *per capita* per day, and *per capita* disposable income, can be used to trace progress toward addressing the direct well-being of people and food security.

A steady increase in the ratio of rural wage to cereal price is a good measurement that poor people may fare well under a scenario, as is the case in most of the scenarios. However, the Rocky Road stands out as the one scenario expected to have a declining ratio down the track, an indication of likely worsening well-being for the poor in this scenario.

Changes in calorie consumption *per capita* per day show another different picture across regions. This indicator was discussed in detail in the previous section.

The *per capita* disposable income (income adjusted for tax payments) is, to some extent, linked to *per capita* GDP growth, and as such, relatively high growth in *per capita* GDP in the Green Road. Bangladesh, in this pathway, sees relatively high growth in *per capita* disposable income, indicative of potential large improvements in the well-being of the overall population in the Green Road. In contrast, the lower-income pathways (Rocky Road and Divided Road) are expected to experience slower growth in *per capita* disposable income.

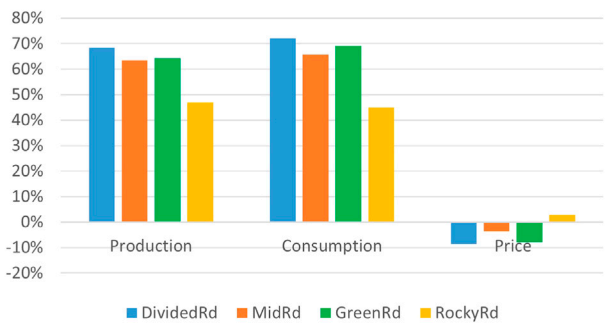


FIGURE 5
Percentage change in production, consumption, and prices of agri-food commodities in 2050 compared to the base year (2011).

### 4.3.2 Prosperity

Prosperity-related SDG indicators are mainly used to measure the economic performance of a region. Derived from SDG modules 7 and 8, we report indicators defined as the change in net trade position and final energy consumption and relate these indicators to some other variables discussed earlier.

Change in the net trade position, despite not painting a full picture of an economy, sheds light on whether a region or certain sectors in a region may become more or less competitive than other regions. This indicator suggests declining competitiveness across all the scenarios (Figure 13), which may be explained by the rising costs in domestic production. It is noteworthy that the Green Road shows the highest decline among all the other scenarios, which clearly shows a trade-off with gains toward SDG2 targets.

**TABLE 4 Scenario quantification assumptions in MAGNET.**

| Narratives | Assumptions | ZHZE scenarios for BGD | Green road | Middle Road | Divided Road | Rocky Road |
|---|---|---|---|---|---|---|
| | | Global contextual scenarios | SSP1 | SSP2 | SSP4 | SSP3 |
| *Socio-economic assumptions* | GDP/Capital growth | Standard SSP shocks | 2 - Good economic growth at a slow pace. Less focus on GDP as a measure of economic growth and more on inclusiveness and environmental stability. | 2 - Economic growth is as it is today for a decade and then slows down because of environmental degradation and the impacts of climate change. | 3 - huge emphasis on economic growth, big push for economic growth and good services and healthy environment for the middle class. Rest of the population (low earners) suffer from the impacts of economic growth from non environmentall friendly options. | 0 - lower economic growth than today and slowing down. Economic growth in the black economy; wealth generated from the black market are not reflected in the national accounts. |
| | Population/ Labour growth | standard SSP shocks | 2 - population growth Is the lower; women's empowerment leads to less population growth in this scenario. | 3 - population growth quite high; women are not as easily included in the workforce and are less empowered. | 2 - women are equally included in the workforce but their working conditions have not improved much. The middle class families are smaller but the family sizes for the lower income population have not declined much. | 4 - women are not included in the work force, little emphasis on education on women;s education. Lot of unskilled labour, many children are ensured to for survival. |
| | Fossil fuel prices | Will result from CO2 price and other assumptions | 1 - Fossil fuel prices decreasing as alternative energy availability increases. | 3 - Still heavily dependent on fossil fuel imports, prices quite volatile. | 2 - More push for alternative sources but also a greater demand for fossil fuel. Volatility reduced because of improved infrastructure and more stable supply of fossil fuel from SEA. | 1 - Access to energy highly unequal and arbitrary. Prices are erratic due to decreased supply and depend on where location. |
| *Productivity* | Land productivity: agri production per | standard SSP shocks | 2 - slow growth and a push for productivity | 3 - high productivity driven by inputs. Push | 3 - Land productivity is unequal. People | 1 - unequal distribution of |

(Continued on following page)

**TABLE 4 (*Continued*) Scenario quantification assumptions in MAGNET.**

| Narratives | Assumptions | ZHZE scenarios for BGD | Green road | Middle Road | Divided Road | Rocky Road |
|---|---|---|---|---|---|---|
| | | Global contextual scenarios | SSP1 | SSP2 | SSP4 | SSP3 |
| | hectare (or any unit of land) | | but within ecological limits. | for intensification but ecological roadblocks limit productivity eventually. | without capital to invest become less productivity. Access to food is then reduced by the unavailibility of lack of income from waged rural labour. | productivity due to the fragmented nature of the country. |
| | Feed productivity (efficiency): feed use per unit of livestock production | standard SSP shocks | 4 - feed productivity essential to the success of the agro ecological system. | 3 - Different kind of technical change, there is a slow pace of growth in productivity because of patchy implementation of policy. | 4 - Feed productivity highly efficient; modern technology and advances help improve livestock. | 2 - slow technological growth, feed available is not very efficient even though a lot of people own cows. |
| | Productivity of fuel in transport: use of (fossil) fuels per kilometre | S4N shocks | 3 - push towards more efficient technology and fossil fuel use. Takes a while to implement these inclusive processes and ensure widespread adoption. | 1 - productivity of fuel in transport deteriorating due to the lack of availability and higher prices of fuel. | 4 - push towards highly efficient and advanced technology and alternative fuel that can be easily implemented by the authoritarian regimes. Better roads and infrastructure leading to less congestion and greater fuel efficiency. | 1 - Not very different from today. While new technology is becoming available the change is very sporadic and not widely adopted. |
| | Productivity of inputs in productions of renewable energy | S4N shocks | 3 - Push for RE to be deployed and made accessible for everyone. | 1 - lack of finance and governance and the SHS drive has slowed down. | 3 - high availability of technology and implementation of RE policies and governance. | 1 - Highly unequal access to RE technology; very individualistic no push by the government for RE. |
| *Regulations* | Afforestation (agricultural area converted to forest) | asymptote shocks | 4 - Assuming this includes agro forestry. | 2 - mixed picture, some afforestation but not enough, depletion of Sunderbans. | 2 - only focus of afforestation is for tree crop exports (fruits; wood); local demand for fruit and veg also increase so more of a focus for the use of land for agriculture. | 1 - more people on smaller pockets of land contributing to deforestation. Drug keeping/making areas forested for growing illegal crops. |
| | Energy efficiency (for example biofuel mandates of renewable energy directive) | The legislation will allow the use of 5% ethanol with conventional fuels, but does not mandate production levels. | 3 - strong push for mandates but implementation not as successful. | 2 - very much like the present picture. Many energy efficiency mandates present but implementation has not been possible. | 3 - government led push for energy efficiency regulations but strong backlash from private international corporations. | 1 - old fashioned factories have not been updated; high polluting and lack of modern efficient infrastructure. Lack of availability of modern energy technology/use. |
| *Policy* | Agricultural policy (e.g. subsidies) | scenario specific | 3 - Big push for agriculture to become more productive but within ecological limits. Different policy instruments to support that and incentivise such a move. (Would | 3 - Focus on food security, large scale subsidies for energy and fertilizers for agriculture. | 2 - Not as protected, more of a push for market based instruements and large scale agriculture. Opening up land ownership to land investors by the private | 1 - Little push for agriculture protection. Not much power to implement the existing policies. |

(Continued on following page)

**TABLE 4 (*Continued*) Scenario quantification assumptions in MAGNET.**

| Narratives | Assumptions | ZHZE scenarios for BGD | Green road | Middle Road | Divided Road | Rocky Road |
|---|---|---|---|---|---|---|
| | | Global contextual scenarios | SSP1 | SSP2 | SSP4 | SSP3 |
| | | | like this to reflect food security and not just agriculture policy?) | | sector, less regulation by government. Aim is to get FDI. | |
| | Trade (tariffs and subsidies) and trade agreement with other regions | scenario specific | 2 - Still need to import rice while the effects of agro ecology take place. Some protection for national agriculture while the effects of the implemented policies get stronger. Modernisation of RGM sector alongside labour rights makes the sector and exports more productive but slowly. | 2 - advances have been made to ensure rice security but there is still a need for imported rice to ensure food security for the growing population under growing environmental degradation. RMG industry unlikely to meet its potential. Little diversification of the RMG industry. | 3 - imports from SEA and integration with the Chinese market. Open market, fruit and veg grown for export but a lot of rice in imported. There is diversification from the RMG industry into the ICT sector but it is a very unequal society so its still leaves many people behind in an unreformed RMG sector with fewer labour rights. | 1 - a lot of black market trade takes place, tax revenues are reduced even further. Some people will get very rich but the majority of the population suffers. Protection of certain high value crops that bring in a lot of money increases because of power elites. Other food stables will be highly neglected. Overall trade openness but very patchy implementation and a lot of diversion of revenues from corruption. |
| | Climate policy: carbon tax on emissions, emission quotas, and subsidies for bio-based energy | Emission reduction according INDC of Bangladesh. 5% by 2030 in industry and services or 10% (all sectors) with international help | 4 - all policy and financial instruments are exploited to get climate change under control. (What happens to the international climate finance regime?) | 2 - Some policies exist but there is a lack of implementation making it ineffective. Implementation here depends on the availability international climate finance. | 3 - lot of top down implementation of climate change policy initiatives. | 1 - few policies exist but implementing them to tackle climate change is not a priority. |
| *Intrinsic motivation* | Trends in meat consumption | Consumer preference shock-->Would a reduction of for example 20% to compare with trend is sensible for BGD? Expected trend generated by scenario assumptions will be increase of meat consumption. | 1 - meat consumption goes down as part of a healthy and sustainable livestyle but eggs, fish and dairy consumption increases. Push towards reducing the meat consumption of the rich. | 3 - continuation of an increase in meat consumption, poor people aspire for the food intake similar to the rich. | 2 -mean consumption amongst the rich people increases. | 3 - Huge split in the consumption of meat, only the rich mafia are able to afford and control the availability of meat. |
| | Consumer preference shifts (Household Energy savings) | Consumer preference shocks | 4 - increase in energy efficiency, energy savings and RE. People are very aware of their choices and its impact on the environment. Governemnt support, education and awareness raising schemes for behavioural change. | 2 - starting awareness but little incentives for behavioural change, very dependent on individual choices. | 2 - government is more interested in investing resources for economic growth rather than environmentally friendly initiatives. Consumerism is encouraged, any changes in behavioural change is very much an individual choice. | 1 - inadvertent energy savings as part of a move towards savings by small pockets of general population. |

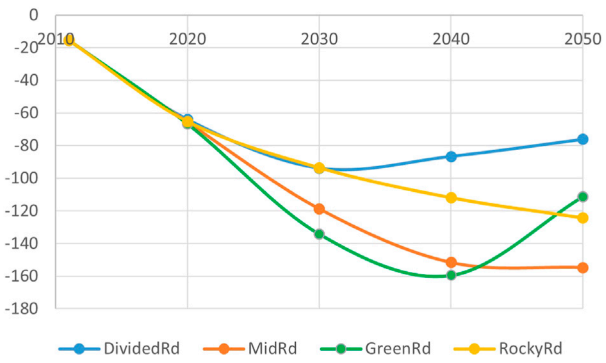


**FIGURE 6**
Net export value of total agri-food commodities.

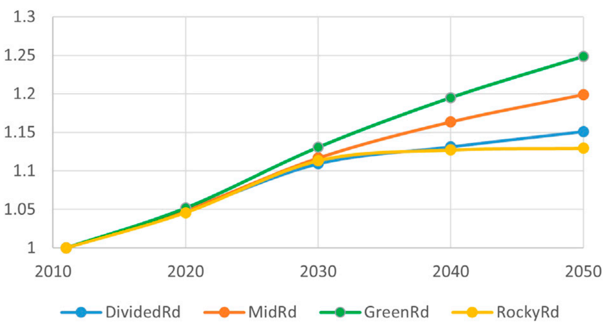


**FIGURE 7**
Food availability index (2011 = 1) measured by kcal *per capita* per day available for consumption.

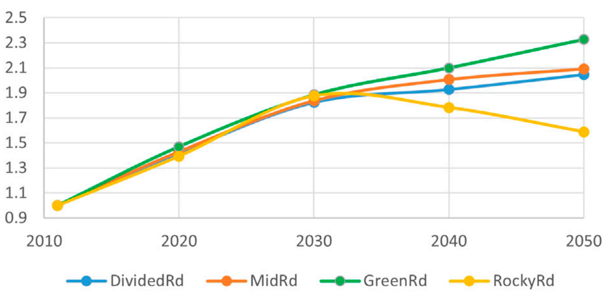


**FIGURE 8**
Food accessibility index (2011 = 1) measured in food purchasing power cereals for unskilled agricultural workers.

Final energy consumption is a gauge for access to energy, a measurement consistent with the SDG7 goal—ensure access to affordable, reliable, sustainable, and modern energy for all.

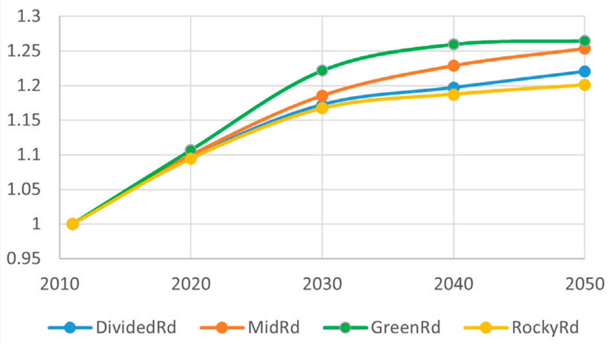


**FIGURE 9**
Food utilization index (2011 = 1) measures in the share of calories derived from fruits and vegetables.

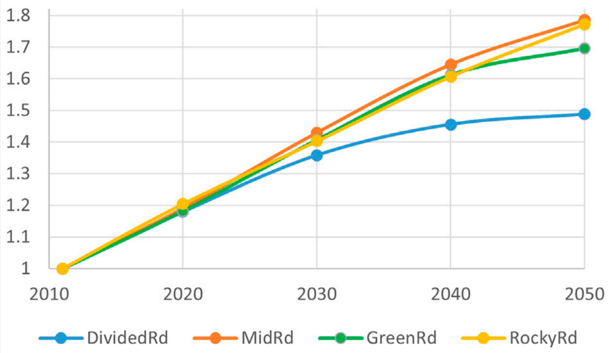


**FIGURE 10**
GHG emission in agri-food sectors CO2 equivalent index (2011 = 1).

Projections on final energy consumption show that higher-income scenarios, Green Road and Mid Road, are expected to experience higher growth in final energy consumption, while the growth trend in lower-income scenarios is less pronounced.

### 4.3.3 Planet

Planet-related indicators derived from relevant SDG modules (SDGs 9, 12, and 13) measure the extent to which changes in economic activities may become more environmentally friendly. Among other candidates, GHG emissions per unit of GDP, sectoral emissions per unit of value added, and the share of renewable energy in total energy production are reported as measurements for an environment-oriented check.

As an alternative measurement for emissions intensity, emissions per unit of GDP are expected to edge lower in all the scenarios (Figure 13), especially in the Green Road, indicative of economic growth in this scenario being compounded with substantial technological progress rendering commodity production becoming less reliant on energy inputs. This is

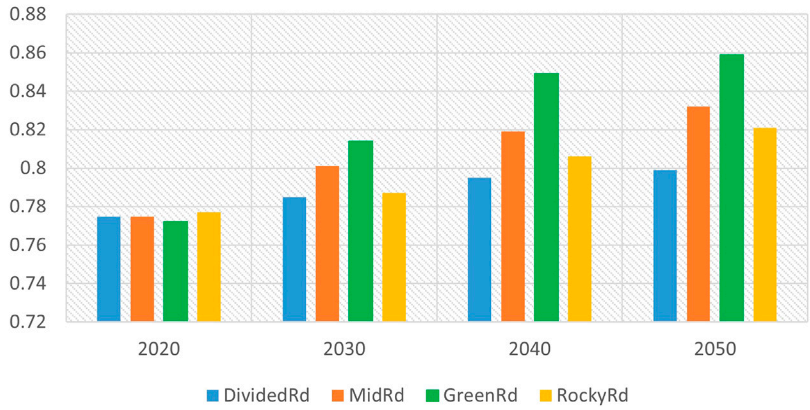


**FIGURE 11**
Land pressure and agricultural land use percentage of total available land.

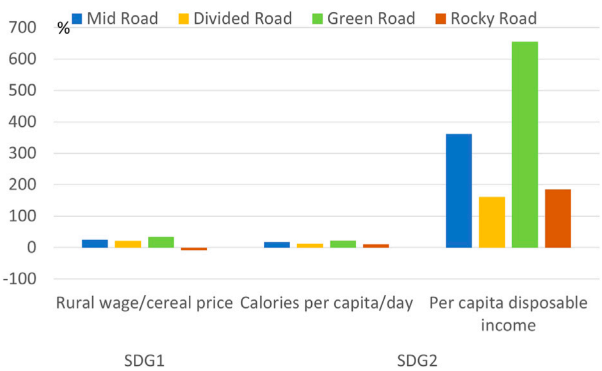


**FIGURE 12**
SDG 1 and SDG 2 insight indicator growth in 2050: % change in 2050 compared to the base year 2011.

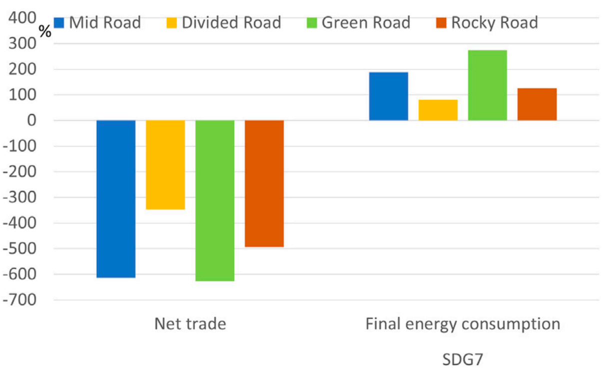


**FIGURE 13**
SDG 7 insight indicator growth: % change in 2050 compared to the base year 2011.

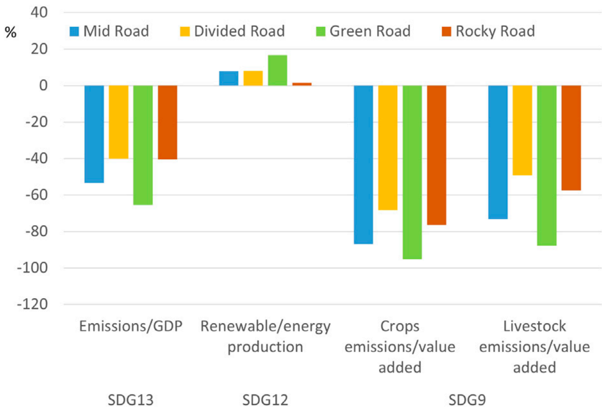


**FIGURE 14**
SDG 13, SDG 12, SDG 9 insight indicator growth: % change in 2050 compared to the base year 2011.

consistent with broad assumptions made for the baseline, including not only explicit technological progress shocks (e.g., land productivity shocks), but also implicit technological progress built into assumed GDP and population growth. Given the Green Road trajectory, GDP growth may only be partially sustained by the assumed population growth. Thus, this part of the built-in technical progress also contributes to the efficiency gain in energy use and consequently less GHG emissions in the economy.

At the sectoral level, GHG emissions per unit of value added in crops and livestock sectors also show a declining trend across regions. Given the overall declining emissions per unit of GDP, these sectoral results are unsurprising, as these sectoral measurements are simply the decomposition of the

Bangladesh country-level measurement, and the reported sectoral results show a consistent trend (Figure 14).

For the share of renewable energy production in total energy production (see Figure 14), all scenarios are expected to experience an increasing share of renewable energy production. In the case of the Rocky Road, the growth is very low as this is the only scenario in which Bangladesh does not meet the NDC GHG emission targets in 2030. Even the growth in Green Road is only 18%, which is much lower than expected. The impact can also be seen in the high total GHG emission in this scenario, which was reported in the previous sections, suggesting that despite the expected fast growth in renewable energy sectors, the assumed renewable energy trajectories in the Green Road, underpinned by, among other things, implemented biofuels and bioelectricity policy shocks and meeting the highest NDC target by 2030 remain insufficient to increase the share of renewables amongst the energy mix (Figure 14). This highlights another trade-off between rapid economic growth and higher food security and the greening of the economy in the Green Road.

## 5 Conclusion and future prospects

The scenario work portraying different futures for the Bangladeshi food system shows that diverse pathways for the country are possible, each with differing and far-reaching consequences for food security (SDG 2) and low-carbon development (SDG 13). In general, the scenario results point to similar directions, although they vary in the magnitude and speed of projected changes.

With respect to achieving food security for Bangladesh by 2050 (SDG2), all described pathways make progress toward this goal but at different paces. The Green Road scenario shows the biggest increase, whereas the Rocky Road pathway, characterized by both reactive environmental management and difficult governance circumstance, shows the smallest improvement. Interestingly, the Divided Road scenario only scores a bit better than the Rocky Road scenario, pointing to large differences across the population with respect to food availability. One question that arises here is whether the higher availability of food translates into better nutritional outcomes across the population. The current Bangladeshi diet is relatively low in fresh fruit and vegetable consumption. The Green Road scenario, with its emphasis on strong environmental stewardship and the SDGs, fares quite well in this aspect compared to the other scenarios. However, the overall intake of fruits and vegetables is insufficient to meet healthy consumption targets. This points to the fact that higher availability needs to be combined with a shift in consumer behavior and better access. With respect to food accessibility, the Green Road fares the best again, followed by the Divided and Middle Roads, all of which show an increase in access to food for the population up to 2050. In the Rocky Road, the disintegration of governance and patchiness of economic development led to an overall decline in food accessibility, as substantial parts of the population would struggle to make a living and afford food. However, these results point to the need for further disaggregation of food accessibility data for all scenarios but particularly for the Rocky and Divided Road scenarios to better understand the difference across the whole population.

With respect to climate action for SDG 13 and the Paris Agreement, the total GHG emissions of Bangladesh will not go down completely in any of the scenarios. Although growing efficiency per unit of output will help bring down emissions trajectories, even in the scenario with the strongest proactive environmental management (Green Road), GHG emissions will not reach zero by 2050. In this scenario, gains in efficiency per unit of output will be outpaced by growing emissions due to economic growth. This finding is an important result with far-reaching implications for policymaking as it points to the delicate balance that policymakers will have to strike between the type of economic growth pathway they are choosing and GHG mitigation goals that an emerging economy such as Bangladesh might have to comply with in the future. This points to the difficult choices policymakers will have to make between short-term gains in human well-being and long-term planetary health objectives.

Furthermore, the Green Road scenarios show another important trade-off that might arise in the future, namely, the issue of growing land pressure that this scenario shows despite strong proactive management of natural resources. This results from a combination of agricultural extensification measures and strong income growth in addition to a rise in agricultural exports in the scenario. This interaction of important drivers of land use change exposes the need for strong environmental policies and their implementation for safeguarding biodiversity.

The scenario analysis presented in this paper on possible pathways for Bangladesh presents options for achieving both food security and climate actions simultaneously (see the Green Road scenario). This requires not just strong action around environmental stewardship and management but also the implementation of policies *via* a well-functioning governance system and the political will to move into a more sustainable trajectory. The analysis also cautions against the assumption that these goals can be achieved without focusing on the type of economic growth pathways sought for Bangladesh or the several other driving forces that will determine the balance between both goals. At the same time, the results also point to the need for close attention to the impact that food security and climate policies might have on the achievements of other goals and the need for an inclusive debate within the country on how to achieve a "good" balance between the various goals that the SDGs have put on the table, as there will be "no free lunch," i.e., trade-off decisions will have to be made across the various goals.

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The recent crises caused by the COVID-19 pandemic and the Ukraine war are causing disruptions in global food supplies with grave consequences. Recent evidence shows that the world is moving backward in achieving many SDG 2 targets leaving the world with an even larger gap to the targets set for 2030 (FAO, IFAD UNICEF, WFP, and WHO, 2020). Although these crises are considered short-run supply shocks, the consequences on food security are likely to be longer-lived, and other similar shocks in the future cannot be discounted. Therefore, effective scenario foresight modeling of food security is needed to better anticipate these types of shock to the food system. However, the parametric values of the MAGNET model used in this study and, in general, the CGE models are equipped by default for long-run scenario analyses, where the time horizons under consideration are typically 5 years or longer. To assess an economic impact spanning shorter time horizons, these types of models will need to be reparametrized to better simulate short-run behavior. There remain many research areas for the future to enhance the treatment of a severe crisis such as COVID-19. The first is to enhance the weakness of CGE models such as modeling demand-side shocks and include better monetary and fiscal policies. Second, a better assessment of food access requires an explicit household dimension in the model to cover both income and food expenditures at a specific household level. Moreover, the importance of transition possibilities of labor from agriculture to other sectors and lock-in effects in segmented labor markets is crucial. Moreover, for a better assessment of the food utilization dimension, the explicit modeling of micro- and macronutrients at the household level is needed in combination with clear guidelines for healthy diets.

## Data availability statement

The data analyzed in this study are subject to the following licenses/restrictions: The dataset on which this paper is based on are too large to be retained or publicly archived with available resources. They are also with restricted access. Documentation and methods used to support this study are available from GTAP 9 Database (https://www.gtap.agecon.purdue.edu/databases/v9/default.asp), SSP database (https://tntcat.iiasa.ac.at/SspDb/dsd?Action=htmlpage&page=about), and Bangladesh Household and Expenditure Survey (HIES 2011) data (http://data.bbs.gov.bd/index.php/catalog/HIES). Requests to access these datasets should be directed to SM, saeed.moghayer@wur.nl.

## Ethics statement

Ethics review and approval/written informed consent was not required as per local legislation and institutional requirements.

## Author contributions

SM: conceptualization, methodology, modeling work, and writing—original draft. MZ and MM: scenario conceptualization and development, writing. JM: scenario development and narratives. DM-D: data and modeling, writing. AT: model development and simulations. JV: conceptualization, scenarios, and writing (revision). TA: conceptualization, framework, and writing (revision).

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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/fenvs.2022.977760/full#supplementary-material

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# Grounding United States policies and programs in soil carbon science: strengths, limitations, and opportunities

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The advent of "natural climate solutions" and "climate smart agriculture" has increased interest in managing agricultural lands to sequester soil carbon and mitigate climate change. This has led to enormous opportunities for soil scientists and growers alike, as new soil carbon initiatives are created by public, private, and philanthropic entities. It has also led to confusion over what is possible or practical to achieve through agricultural management, as soil carbon formation and storage is complex, and its response to management is context-dependent. This can pose challenges to decision makers tasked with creating defensible, science-informed policies and programs for building and protecting soil carbon. Here we summarize the science concerning the potential for agricultural soils to serve as a natural climate solution, in order to frame a discussion of current approaches in United States (US) policy and practice. We examine existing strategies such as soil health initiatives and direct incentive payments, as well as emerging schemes such as carbon markets and crop insurance reform. We suggest future directions for each strategy, and make recommendations for synthesizing approaches into a cohesive US policy portfolio. Guiding principles for this discussion include the notions that (i) climate change adaptation must be prioritized alongside climate change mitigation; (ii) soil carbon sequestration must be paired with greenhouse gas emission reductions; (iii) structural issues and barriers to adoption must be addressed as part of all policies and programs; (iv) practice- and place-specific programs must be administered in lieu of one-size-fits-all prescriptions; and (v) soil carbon science is not yet sufficiently advanced for the accounting and contractual frameworks proposed in cap-and-trade or regulatory approaches.

KEYWORDS
**carbon sequestration, policy, regenerative agriculture, climate smart agriculture, climate change, soil carbon**

## 1. Introduction

Soil carbon was historically the subject of niche curiosity, with soil scientists and agronomists alone studying its accumulation and persistence, while progressive growers experimented in their fields (Feller and Bernoux, 2008). The urgency for society to mitigate climate change, however, has sparked intensive interest in managing agricultural land to maximize soil carbon sequestration. With the recent popularization of "regenerative farming" and "climate-smart agriculture," gone are the days in which soil carbon belongs exclusively in the sphere of scientists and farmers (Amundson, 2022). Popular interest in soil carbon is evidenced in star-studded documentaries such as Kiss the Ground, or public outreach campaigns such as Chefs for Healthy Soil. Political and entrepreneurial interest is also clear in the enormous investments that governments, businesses, and nonprofits are making (Kreibich and Hermwille, 2021; Marston, 2022). For decision makers who have not spent their careers studying the minutiae of soil carbon, recent activity may beg the questions: What is soil carbon? Why is it so important? How can I design defensible, science-informed soil carbon policies and programs?

Here we seek to answer these questions for United States (US) practitioners by synthesizing the science, examining current US policy approaches, and outlining future directions. Drawing on the extensive scientific and policy literature on soil carbon, soil health, and natural climate solutions, 10 contemporary US strategies are analyzed in terms of their strengths and limitations. We address limitations by presenting actionable opportunities and highlighting successful programs throughout the US. We conclude by recommending guiding principles intended to build soil carbon and protect soils equitably, responsibly, and in perpetuity. These efforts are used to underscore that soils provide numerous benefits, which are essential for both climate change mitigation *and* climate change adaptation. The overall aim is to provide actionable direction for increasing soil carbon storage, while simultaneously encouraging a more comprehensive and holistic approach to soils in policy and practice.

## 2. Review methodology

Google Scholar was searched using keywords soil carbon OR natural climate solutions AND policy OR soil health, practice, economics, incentives, behavior, crop insurance, modeling, technical assistance, and regulation. Care was taken to include a representative sample of relevant works, with an emphasis on review papers, recent publications, and studies which present divergent perspectives on current controversies. The list of studies included is not exhaustive. The purpose of this narrative review is not to provide a quantitative or systematic assessment, but rather to survey recent and critical literature on this timely topic, and to broaden the contemporary discussion of soils beyond carbon. As such, a broad selection of publications was included which contribute to the overall objectives of encouraging a comprehensive approach to soil conservation in US policy and practice, and to highlight future opportunities. Likewise, the US programs and projects we describe are not exhaustive, but instead selectively presented to provide concrete and replicable examples.

## 3. A synthesis of the science

### 3.1. What is soil carbon?

Collectively, the world's soils hold over three times more carbon than the atmosphere, and nearly double the carbon than in all terrestrial vegetation combined (Oelkers and Cole, 2008; Scharlemann et al., 2014). While soil carbon exists in myriad and diverse configurations, it can be broadly grouped into organic and inorganic forms. Soil organic matter (SOM) is the 1–5% of most soils not made up of minerals, air, and water, but is instead composed of animal and plant tissue in various stages of decomposition. SOM is roughly 58% soil organic carbon (SOC). The remaining portion includes other essential plant nutrients such as nitrogen, phosphorous, and sulfur. Soil inorganic carbon– primarily found in arid environments– also represents an important component of soil carbon (Monger et al., 2015). However, it is generally considered more difficult to increase via management and is a smaller soil carbon fraction than SOC. While some strategies can increase inorganic soil carbon (Kantola et al., 2017; Goll et al., 2021), most discussions of management focus on the carbon in SOM.

### 3.2. How is soil carbon accumulated and stored?

Figure 1 illustrates how atmospheric carbon dioxide ($CO_2$) is converted into SOM through processes driven by plants and microbes (Dynarski et al., 2020; Angst et al., 2021). Plants use $CO_2$ for photosynthesis, converting gaseous carbon to sugars that are stored in plant vegetative bodies, or exuded through plant roots into the soil. Soil microbes use the vegetative carbon in dead plants, leaves, or root exudates—along with dead micro or macro fauna, manure, compost, and other organic materials—as a substrate for metabolism and population growth. Most of the carbon in those organic inputs is converted back into $CO_2$ and released into the atmosphere, while only 3-33% is retained in SOM (Cotrufo and Lavallee, 2022) or microbial bodies (Buckeridge et al., 2022). Over time microbes grow, multiply, and die, leaving behind microbially-processed carbon that can adhere to soil minerals and be protected for variable lengths of time. The biophysical process by which gaseous carbon is drawn down through plants, processed by microbes, and added to soils is called soil carbon sequestration. The amount of carbon sequestered, minus the amount lost, is called soil carbon storage (Jansson et al., 2021).

The uniquely complex processes of soil carbon accumulation and storage have been well described in the scientific literature for decades. For more technical summaries, see Lal (2004), Janzen (2006), Miltner et al. (2012), Crowther et al. (2016), Lavallee et al. (2020), Angst et al. (2021), Feeney et al. (2022), Patoine et al. (2022), and Derrien et al. (2023).

### 3.3. Why is soil carbon so important for climate change mitigation and adaptation?

Increases in soil carbon are associated with numerous potential benefits, one of which is climate change mitigation (Bradford et al., 2019; Vermeulen et al., 2019; Amundson et al., 2022). Immediately halting the loss of existing soil carbon also has a climate impact, by stopping the continued release of $CO_2$ into the atmosphere. Moreover, building and preserving soil carbon can promote the myriad benefits that SOM provides (Figure 1), and is key to helping growers and society adapt to climate change and reduce land use conversion (Kopittke et al., 2022).

Soil organic matter benefits are context-specific, but can include increased fertility and nutrient use efficiency (Tiessen et al., 1994), with the potential to decrease dependence on greenhouse gas (GHG)

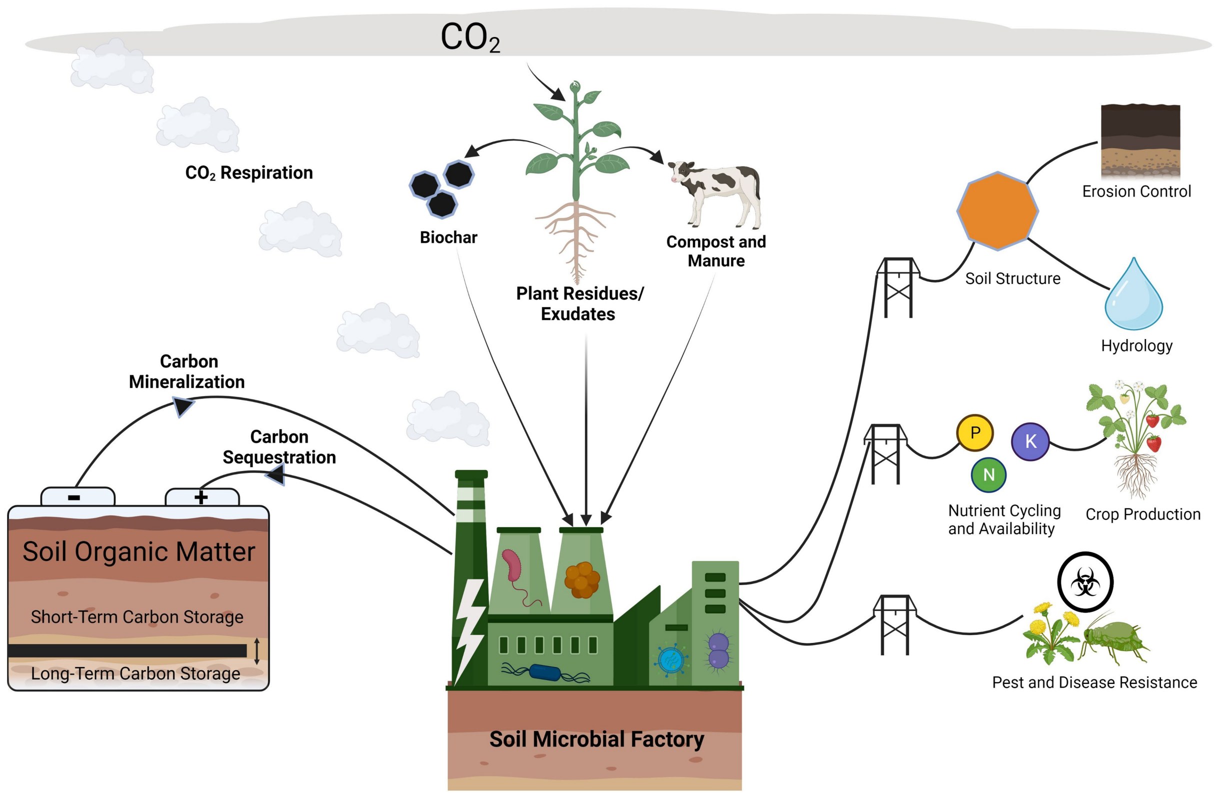


FIGURE 1
Conceptual diagram detailing how soil organic carbon is both accumulated and utilized by soil microbes to power a broad suite of ecosystem services.

intensive fertilizers (Crippa et al., 2021) or increase crop yield per unit of land (frequently called sustainable intensification; Pretty and Bharucha, 2014). SOM can also improve soil structure (Oades, 1984), and therefore increase resistance to wind and water erosion (Barthès and Roose, 2002) and improve air and water quality (Fageria, 2012); improve soil water dynamics including infiltration, filtration, and water holding capacity (Emerson, 1995; Blanco-Canqui et al., 2013); and support soil biodiversity which can drive several vital functions such as residue decomposition, carbon and nitrogen cycling, and disease resistance (Schlatter et al., 2017; Delgado-Baquerizo et al., 2020). Independent of soil carbon or SOM, broadly protecting soils preserves wildlife habitat, recreation sites, cultural heritage, archeological records, and rural livelihoods.

## 3.4. How does agricultural management impact soil carbon?

Because agriculture is often referred to as a "natural climate solution," a pervasive notion has emerged that climate change can be reversed by changing "bad" farming practices to "good" farming practices (e.g., conventional tillage to no-till). This notion overlooks the fact that carbon has substantially decreased in the vast majority of soils converted from unmanaged to agricultural land (Guo and Gifford, 2002; Scharlemann et al., 2014; Sanderman et al., 2017). Soils are indeed an important soil carbon store, and naturally low-carbon soils may sustain increases as the result of agricultural management (Sanderman et al., 2017). However, agriculture necessarily and inherently exploits soil carbon for crop production. Reversing climate change purely via soil carbon sequestration is not a feasible goal. Instead, it is feasible to regenerate soil carbon in many conditions, and to immediately halt the further loss of this invaluable carbon store.

Agricultural activities can diminish soil carbon stocks by reducing carbon inputs, and by increasing pathways for loss. Modern agriculture exports more carbon than it sequesters, through crop genetics (e.g., varieties that promote the growth of harvested grain or fruits rather than roots and root exudates; Jansson et al., 2010, 2021), and through management (e.g., removing crop residues rather than returning them to the field; Stella et al., 2019). Microbial processing, or mineralization, of SOM is necessary to supply valuable nutrients to crops. However, this process converts soil carbon back into $CO_2$. The very same microbes responsible for building soil carbon must also deplete it to survive and to support plant growth, in an ongoing cycle of microbial and soil carbon turnover (Figure 1; Dynarski et al., 2020). SOM mineralization in the face of reduced carbon inputs diminishes soil carbon stocks, which can be further compounded by management: Mechanical tillage exposes once protected carbon to oxidation, mineralization, and erosion (Huggins and Reganold, 2008; Chowaniak et al., 2020; Yu et al., 2020); the burning of crop residues can destroy SOM (Collins et al., 1992); irrigation can result in soluble carbon leaching through the soil (Moore, 1997; McTiernan et al., 2001; Ruark et al., 2009; Shang et al., 2018; Sagar and Singh, 2020); and soil not held in place by ground cover or living roots, such as in fallowed fields, can be lost through runoff or erosion, carrying carbon with it (Sharratt et al., 2018).

Agricultural management can also increase soil carbon, or be tailored to protect existing carbon stocks. Terms like "regenerative farming" and "climate-smart agriculture" are frequently used to define a suite of practices aimed at optimizing crop production while protecting and building SOM. Practices include reduced tillage, reduced fallowing, cover cropping, livestock integration, adding carbon-based amendments (e.g., manure, compost, crop residues, or biochar), breeding crop varieties that produce more roots and root exudates, conservation crop rotation, agroforestry, and retiring marginal lands from production.

While these practices can deliver many on-farm benefits, they are not one-size-fits-all solutions for increasing soil carbon. For example, conservation tillage has been observed to increase (Bai et al., 2019; Ogle et al., 2019), decrease (Ogle et al., 2012), and have no effect on (Luo et al., 2010) soil carbon. In fact, one meta-analysis determined that conservation tillage reduced crop yield by an average of 5.1% across all crops and conditions evaluated (Pittelkow et al., 2015). Reduced crop yields may require more land be converted to agricultural production, which results in a net soil carbon loss overall (Guo and Gifford, 2002; Sanderman et al., 2017). The impact of cover cropping on soil carbon has also been observed to be condition-specific, with greater effects in fine-textured soils and when a legume is present in the cover crop species mix (Jian et al., 2020).

Further complicating carbon sequestration potential is that other essential nutrients (e.g., nitrogen, phosphorous, and sulfur) are required for the conversion of carbon inputs into SOM. This elemental balance, or stoichiometry, may even dictate whether carbon is respired as $CO_2$ or transformed into microbial cells. Therefore, practices that literally add carbon to the soil do not necessarily build SOM or achieve carbon sequestration, if other necessary inputs are not also present (Schlesinger, 2022). Additionally, potential increases in soil carbon are not infinite, with many soils having a natural equilibrium or saturation point, after which gains as the result of management can plateau (Stewart et al., 2008).

While the potential for management to increase soil carbon is limited by environmental factors such as soil texture, nutrient content, and climate, it is also limited by social factors such as technical assistance availability, crop prices, and farmer culture. Management decisions, which are themselves the product of complex cultural and socioeconomic factors, play a significant role in balancing the tradeoffs between crop production and ecosystem services (Carlisle, 2016; Teixeira et al., 2018; Wade et al., 2021). These facts underscore the need for place-based research that considers not only the soil and climate context, but what unique barriers a grower may face in a particular region or cropping system. They also underscore the need to measure multiple outcomes including water and nutrient cycling and filtration, biodiversity support, crop production, farmer innovation and attitudes, climate change mitigation, and negative externalities.

## 3.5. Why is it so difficult to account for soil carbon?

There are many challenges in measuring soil carbon, estimating how long it will last, and quantifying increases that result from altered management (Chenu et al., 2019; Stanley et al., 2023). This is due to soil heterogeneity, the costs of comprehensive sampling, and the uncertainty associated with laboratory analysis methods and the use of models.

Soils accumulate and store carbon differently based on texture, depth, mineralogy, and climate, even within a single field (Wiesmeier et al., 2019; Basile-Doelsch et al., 2020). Taking sufficient samples to account for variability can be prohibitively labor- and cost-intensive. For example, it is common to sample only from the soil surface, despite the sizeable carbon stocks that may exist deeper in the soil profile (Gross and Harrison, 2019). This can lead to erroneous conclusions that carbon is being lost or gained as the result of management, when it has actually been vertically redistributed (Baker et al., 2007; Gál et al., 2007). In addition, soil carbon can be seasonally variable, with measurements differing by when in the year a sample is taken (Wuest, 2014).

There is also heterogeneity in analytical methods, which can lead to inconsistent results and interpretations among laboratories and statisticians (Wade et al., 2020; Crookston et al., 2021; Slessarev et al., 2023). Some methods can describe how much carbon is in the soil while providing little insight on how long it will be last. This is because soil carbon is stored in many forms, some of which are more protected from degradation than others (Lavallee et al., 2020). A single measurement may suggest a high carbon content, even if the carbon is mostly in plant residues and will soon be respired as $CO_2$. This also raises the issue of non-permanence, in which gains in soil carbon can be measured, but then quickly reversed through management changes like an increase in tillage or fallowing (Smith, 2005; Dynarski et al., 2020). There are an increasing number of laboratory tests aimed at determining the quantity and stability of carbon stored in multiple forms (Stott, 2019). However, these tests can be resource-intensive to measure, and their correct interpretation is still in question.

Fortunately there have been a number of scientific and technological advances in soil carbon measurement and estimation, which is necessary for effective management and policy formulation (Paustian et al., 2019; Smith et al., 2020). These include the application of pedometrics– the branch of soil science which relies on statistical, mathematical, and big data applications– in soil carbon estimation (Finke, 2012); more accurate models due to the inclusion of machine learning (Keskin et al., 2019; Nguyen, 2021) or multimodel ensembles (Wallach et al., 2018); new high throughput and cost-effective measurement techniques such as spectroscopy (Ball et al., 2020; Barthès and Chotte, 2021) or remote sensing (Thaler et al., 2019); and increased efforts among practitioners to standardize soil databases across projects and regions (Norris et al., 2020).

## 3.6. Should our policies focus on soil carbon alone?

An exclusive policy focus on soil carbon for climate change mitigation devalues SOM co-benefits as incidental byproducts (Figure 2). In reality, these benefits are essential for adaptation to and resilience through current and future climate conditions. The sole focus on carbon also overlooks nitrogen's contribution to climate change, with nitrous oxide having nearly 300 times the impact on global warming as $CO_2$ (Forster et al., 2021). Reducing nitrous oxide emissions from the use of fertilizer and manure via precision agriculture or variable rate technology can play a major role in

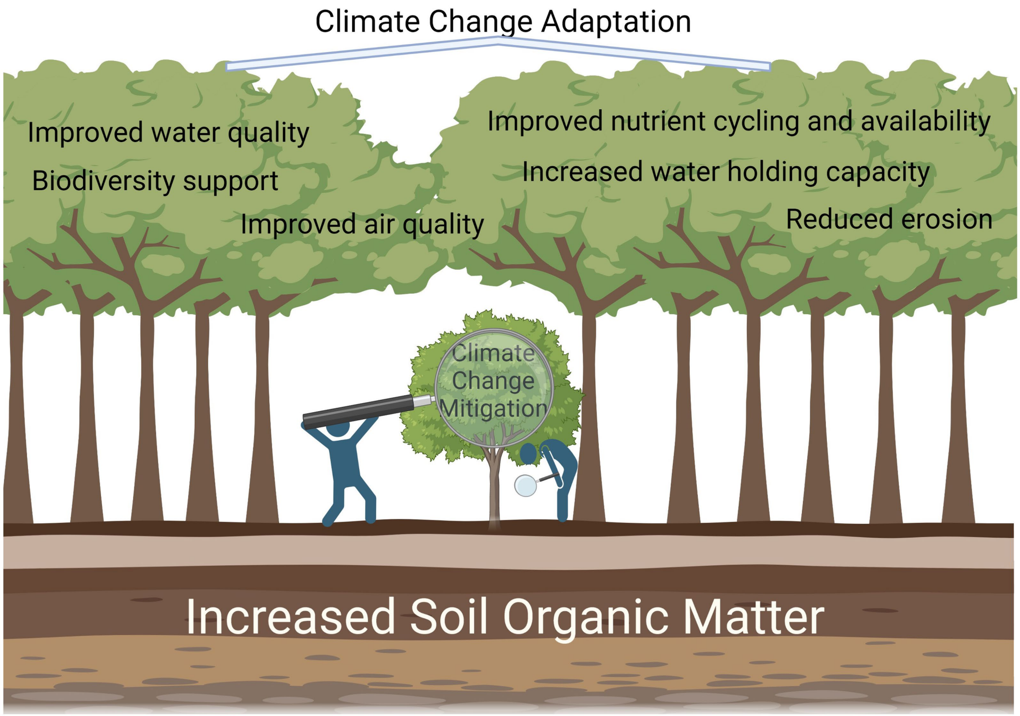


FIGURE 2
Missing the forest for the trees. This conceptual diagram illustrates how policies with a sole focus on increasing soil carbon for climate change mitigation may miss opportunities to promote other ecosystem services. Improving agricultural management can improve the capacity for growers and society to adapt to climate change, even in cases where it does not mitigate climate change.

climate change mitigation, alongside sequestering soil carbon through cover cropping or reduced tillage (Skiba and Rees, 2014; Winiwarter and Mohankumar, 2015; Schulte-Uebbing et al., 2022). Policies and programs that protect soil and improve soil management– independent of the direct impact on soil carbon– are more likely to promote ecosystem services while simultaneously reducing GHGs.

## 4. Current approaches in policy and practice

While soil carbon is a relatively new policy domain, broadly protecting soils has long had its place in the US (United States Department of Agriculture, n.d.). Laws include the National Industrial Recovery Act of 1933, which created the Soil Erosion Service; the Soil Conservation Act of 1935, which created the Soil Conservation Service [known as the Natural Resources Conservation Service (NRCS) since 1994]; the Soil and Water Resources Conservation Act of 1977; and the Food Security Act of 1985. Additional soil-specific programs have been created through US Farm Bills, including the Conservation Reserve Program in 1985 and the Wetland Reserve Program in 1990. There is evidence that many of these laws resulted in increased soil carbon (Gebhart et al., 1994; Barker et al., 1996), though this was incidental to their primary goals of erosion prevention and resource conservation.

In contemporary lawmaking, increasing soil carbon is more explicitly at the center of policies and programs. Here we present current US approaches in terms of their strengths, limitations, and future opportunities. This analysis is informed by the state of knowledge of and limitations in soil carbon science and practice adoption sociology discussed in Section 3. It is presented within an overarching framework in which science should inform policy, which should support practice, which in turn should improve science. The objective is to aid decision makers in developing a science-informed policy portfolio that incorporates multiple complimentary approaches, and can be successfully integrated into this framework.

### 4.1. Soil health initiatives

Perhaps the most high-profile US strategy for protecting and increasing soil carbon is the creation of state-specific soil health initiatives. By 2021, twenty states formalized soil health initiatives through resolutions and laws, with an additional twenty signaling interest through related policy activity (State Healthy Soil Policy Map, 2021). Initiatives vary greatly in their level of funding, focus on stakeholder engagement, and projects in their portfolios.

#### 4.1.1. Strengths

Because soil health is focused broadly on the soil's capacity to provide multiple functions (Janzen et al., 2021), soil health initiatives can provide a flexible policy approach to reach beyond carbon sequestration. This is especially meaningful as the potential for agronomic co-benefits is more likely to motivate farmer adoption of conservation practices than the promise of payments for increased soil carbon (Buck and Palumbo-Compton, 2022). The flexibility of soil health initiatives allows programs to be tailored to the needs of specific communities (Warner and Watnick, 2021). Soil health initiatives provide a unifying entity for many other strategies for increasing soil carbon, which can be added to over time with increased funding and engagement.

### 4.1.2. Limitations

The presence of a soil health initiative can signal that action is being taken, even when sufficient levels of funding and engagement are not present. It can therefore have a "greenwashing" effect that reduces the pressure for more immediate action, such as GHG emissions reduction across all sectors (Seddon et al., 2021). There are also challenges in defining and quantifying substantive outcomes of "soil health" (Lehmann et al., 2020; Baveye, 2021a,b; Janzen et al., 2021; Powlson, 2021).

### 4.1.3. Opportunities

The creation of a federal soil health initiative coalition could address capacity differences across the US by facilitating knowledge exchange and the development of region-specific toolkits, best management practices, datasets, and soil carbon models. Cohesive materials and templates could be created for customizable soil health economic studies, survey approaches, data management strategies, and project monitoring and evaluation, among other topics. Furthermore, verified and peer reviewed toolkits for soil health science (e.g., Git repositories containing code for GIS, web, or extension products, and statistical models for project evaluation or climate modeling) could be aggregated and made public. The impact and widespread reliance on USDA tools such as COMET, SSURGO, and conservation technical guides illustrates the potential for central coordination to effectively advance the quality of soil health initiatives (Amundson, 2020). Such efforts are currently underway by groups such as the National Healthy Soils Policy Network, Carbon180, and American Farmland Trust.

## 4.2. Direct incentive payments

Many programs provide growers with grants, financial incentives, and cost share to alter agricultural management. The NRCS was first authorized to provide funding through the Environmental Quality Incentives Program (EQIP) in 1996, and has since distributed over $15 billion to help growers implement conservation practices (United States Department of Agriculture, 2022). Incentive payments can also come from local sources such as the Iowa or Illinois Soil and Water Conservation District Cost Share Programs, or state departments of agriculture as in the California, Maryland, or New Mexico Healthy Soils Programs. Corporations seeking to improve their sustainability portfolio or achieve a net-zero supply chain can also offer direct payments to growers (Marston, 2022).

### 4.2.1. Strengths

Offering financial assistance lowers the barriers to entry for growers to implement conservation practices (Piñeiro et al., 2020). It reduces the risk a grower may experience in experimenting with new practices, and has the potential to mitigate financial losses during transition periods. Financial incentives redistribute the cost of conservation from the grower to the public, who will also reap the benefits of improved air and water quality, carbon sequestration, and food security.

### 4.2.2. Limitations

One-time or short-term financial incentives do not address structural issues such as knowledge gaps, access to equipment, regional climate challenges, or cultural barriers. As such, there is the potential for growers to revert to "business as usual" practices once the grant period is complete (Wallander et al., 2021). Furthermore, resource limitations mean that not all who apply for funding will receive it. For example, only 30% of applicants for NRCS EQIP receive funding, amidst widespread inequities in how funds are distributed across regions, farm size, and demographic groups (Happ, 2021). Incentive programs frequently exclude early adopters, as funding is typically awarded to growers to implement a new practice rather than to sustain one. Additionally, while practices like cover cropping and compost amendment are eligible for funding in many programs, other emerging or experimental practices are not. This can hinder innovation and the development of new knowledge. Finally, contemporary US incentive programs largely reward the implementation of practices rather than the delivery of outcomes. Due to the heterogenous impact of agricultural management on soil carbon, incentive payments cannot uniformly lead to increased soil carbon storage.

### 4.2.3. Opportunities

Increased funding from bills such as the US Inflation Reduction Act can alleviate resource limitations, though may not address structural limitations. Investment in the underlying social and technical infrastructure is also required. Simultaneous investments should be made in research, technical assistance, and market development, as a multi-pronged approach can address structural challenges and extend conservation efforts beyond short-term funding cycles (Bell et al., 2023). Furthermore, funding should be directed towards incentives for emerging and experimental practices. This could reward innovative growers and improve the current state of knowledge. Programs like the USDA AgARDA provide a model that could be adapted for soil carbon research and practice implementation. Despite the drawbacks of practice-based rather than outcomes-based rewards (Weinberg and Claassen, 2006; Bartkowski, 2021), this may be the most feasible policy option pending further scientific advances (Jeffery and Verheijen, 2020). Ideally, practice-based incentive programs would incorporate research partners to advance site-specific soil carbon science, and to ensure that conservation practices are having the desired effect.

## 4.3. Carbon markets

The search for market-based incentives has led to the incorporation of soils in carbon markets, wherein participants can "offset" or "trade" GHG emissions in one sector or geography by increasing soil carbon elsewhere (Croft et al., 2021; Oldfield et al., 2021). Examples include companies that pay a grower to increase soil carbon via cover cropping, in exchange for maintaining or increasing GHG emissions at their factory. The inclusion of soil carbon offsets in carbon markets is controversial, with both supporters and detractors (Vermeulen et al., 2019; Bossio et al., 2020; Kreibich and Hermwille, 2021; National Sustainable Agriculture Coalition, 2021; Zelikova et al., 2021).

### 4.3.1. Strengths

Carbon markets are an innovative iteration of market-based incentives, and may be cost-effective compared to strategies such as direct payments (OECD, 2013). In a properly functioning market, growers can diversify their revenue stream while businesses offset emissions that are otherwise difficult to curb. Continued market valuation could incentivize the sustained use of conservation practices. Furthermore, soil carbon offsets have already proved a driving force of innovation, as evidenced by the enormous investment in soil carbon research and quantification technologies, and the emerging markets for other ecosystem services (Reed, 2020).

### 4.3.2. Limitations

Poor quality standards for carbon trading can lead to a net increase in GHG emissions, if offset purchasers increase their emissions in exchange for soil carbon sequestration that may not be achieved, is difficult to verify, or is reversible. Highlighting this, a recent review ranked 17 protocols used in soil carbon offsets by their rigor, additionality, durability, and grower safeguards (Zelikova et al., 2021). Eight protocols, or nearly 50%, scored only 1 out of 5. Poor quality standards can erode trust between the public or grower communities, and scientists, governments, or NGOs, as observed during the 2010 collapse of the Chicago Climate Exchange (Gosnell et al., 2011). The continued emission of GHGs and other co-pollutants can have serious consequences for the environment, and for the socially or economically disadvantaged communities most likely to live near sources of fossil fuel pollution (Silva and Zhu, 2009; Cushing et al., 2018; Perera and Nadeau, 2022). Furthermore, carbon is frequently priced so low that markets fail to provide sufficient incentives for growers, act as a deterrent for emitters, or allow small operations and lessees to participate (Lundgren et al., 2015; Ervine, 2018; Wongpiyabovorn et al., 2022). Carbon markets also exclude early adopters, and may contribute to a siloed approach to soil protection that focuses only on $CO_2$ drawdown.

### 4.3.3. Opportunities

Soil carbon is dynamic and heterogenous, its permanence is context-specific, and the science of how to build and measure it is evolving. As such, we suggest that soil carbon is not yet robustly quantifiable enough for contractual emissions trading. Soil carbon offsets have indeed been excluded in state-sponsored "cap and trade" carbon markets, such as in California and Washington. There, soil carbon is not *traded* in the market, but rather *invested in* by directing revenue from the sale of GHG emission allowances towards projects that can increase soil carbon. This "cap and invest" strategy promotes soil carbon sequestration as part of market-driven climate change mitigation, but does not depend on it. This approach minimizes potential externalities, keeps in place the pressure to reduce GHG emissions from other sectors, and promotes the formation and protection of soil carbon stocks.

## 4.4. Research

Research programs address uncertainty related to the impact of management on soil carbon by investigating region- and crop-specific contexts. Programs can take multiple forms. Long-term experiments investigate the impact of management practices on soil health, carbon sequestration, and farm profitability over time and under a changing climate. The USDA coordinates a network of 18 such sites in the US, while some states, universities, or community groups coordinate their own regional sites or networks. A common alternative approach are survey studies, such as those carried out by Cornell and the New York Soil Health Initiative (Amsili et al., 2020), Ohio State University (Culman et al., 2022), or the Soil Health Institute (Norris et al., 2020). These projects aggregate data from thousands of soil samples from a variety of real-world contexts, and use statistical analysis to link carbon storage potential to texture, climate, or management. Additional approaches include economic, life cycle, and behavioral studies, which can lead to a better understanding of barriers to adoption, environmental tradeoffs, and practice costs and benefits (Karlen et al., 2017; Stevens, 2018; Brown et al., 2021; Wade et al., 2021).

### 4.4.1. Strengths

Place-based, practice-specific research acknowledges that there is no one-size-fits-all solution, and can lead to science-informed recommendations specific to the climate, soils, and communities of a particular region. Long-term research helps overcome the challenges of soil dynamism and heterogeneity by investigating the impacts of management across time (Riar and Bhullar, 2020). Long-term studies also produce more robust conclusions than those restricted to a 1–5 year grant cycle. Survey studies, on the other hand, are more flexible options, as soil and management data can be obtained from real-world conditions across soil textures, climates, and cropping systems.

### 4.4.2. Limitations

Research is costly, time consuming, and may take multiple years to produce results. Long-term experiments require land to be set aside in perpetuity, which necessitates extraordinary levels of funding and coordination. Furthermore, these sites are geographically static, and can only make inferences about the soils and climates within their boundaries. Additionally, research plots are frequently smaller than typical production farms and may not represent real-world conditions. This can present obstacles to extrapolating conclusions to larger systems, and to disseminating relatable information to growers (Passioura, 2010). Survey studies address these limitations by investigating soils from actual farms across multiple environmental and social contexts. However, this approach also requires significant coordination and investment, as well as special care to reduce variability and maintain data quality across diverse soil sampling and laboratory practitioners.

### 4.4.3. Opportunities

Ideally, long-term research would be paired with survey studies and sociological investigations to produce site-specific knowledge and recommendations. Centrally coordinated research can ensure complementary scientific questions and results, cohesive data management and protocols, and effective public dissemination of results. The Washington Soil Health Initiative provides an example of a multi-agency collaboration with several research strategies in its portfolio. A successful research program integrates the needs, perspectives, and expertise of growers and community stakeholders from the onset (Warner and Watnick, 2021), and works to center practical, economic, and human health considerations. All research efforts should be translated into practice through simultaneous investment in technical assistance, direct incentive payments, and market development.

## 4.5. Model development and improvement efforts

Soil carbon modeling may be a strategy to overcome the challenges of resource-intensive soil sampling campaigns. Models such as Daycent, CropSyst, CQESTR, and COMET-Farm can estimate the carbon sequestration potential of a given practice in a given region, frequently without soil sampling. However, estimation accuracy hinges upon existing sample-based datasets. Therefore, model outputs vary by data quality and availability, as well as by computational differences; the inclusion or exclusion of factors such as future climate, crop type, microbial or mineral influence, plant litter inputs, or soil depth; and whether the user can input site-specific data such as initial measured SOC content (Carey et al., 2016; Crowther et al., 2016; Vereecken et al., 2016; Sulman et al., 2018; van Gestel et al., 2018). Extensive investigation into different models has revealed variable success in making accurate predictions (Vereecken et al., 2016; Sulman et al., 2018). Nevertheless, models can be used to make landscape-scale decisions (Bartkowski et al., 2021), and to enter agricultural operations into carbon markets or direct incentive programs (Oldfield et al., 2021).

### 4.5.1. Strengths

Accurate modeling is essential for any program aimed at building and protecting soil carbon. Models can provide swift, inexpensive estimates of the impact of management. Because many can be run without site-specific measurements, they spare technical assistance providers and producers from taking labor-intensive soil samples year after year, reducing monitoring and verification costs (Paustian et al., 2019). Models can also be used to compare multiple sites, which aids decision makers in prioritizing certain regions or practices to maximize climate change mitigation impacts with limited funding.

### 4.5.2. Limitations

Models have variable success in making accurate predictions, due to the dynamism and heterogeneity of soil carbon, and the numerous differences between models and available data (Vereecken et al., 2016; Sulman et al., 2018). Over-reliance on potentially inaccurate estimates can contribute to similar challenges described with carbon markets, including pollution trading and social inequities. Due to finite resources, difficult decisions must be made on whether to fund the development of new models, or instead improve existing models. This is exemplified by the widely used USDA NRCS COMET-Farm model. COMET-Farm has shown mixed ability to accurately estimate soil carbon changes, does not accommodate measured SOC data, and is difficult to parameterize for many crops and regions (Ball et al., 2023). Nevertheless, the USDA endorses its use, and allocates funding to improving COMET-Farm over models which incorporate emerging and promising technologies such as machine learning or multimodel ensembles. While COMET-Farm has limitations, however, its user-friendly interface enables use by practitioners of mixed technical ability (Paustian et al., 2018). This demonstrates a common tradeoff between ease-of-use and estimation accuracy, with simple models accessible to more practitioners, while more data-intensive and accurate models require advanced knowledge and skill to operate.

### 4.5.3. Opportunities

Increased research dollars from recent US legislation may mitigate the tradeoff between improving existing models or developing new models. Ideally, both could be pursued with a focus on incorporating the latest technologies and improving site-specific estimates. User interfaces and decision-support tools should accompany all models, to increase access for producers, decision makers, and technical assistance providers (Rose et al., 2016). Furthermore, models are only as strong as the datasets they are built from. With central coordination, in-depth literature reviews could be conducted to develop place-based (e.g., watershed, soil type, or contiguous cropping systems as feasible or appropriate) GHG coefficients for each conservation practice. Where literature does not exist, a grant program could be created to address the knowledge gap by funding primary research.

## 4.6. Technical assistance

Technical assistance, or practical support to growers in the form of resource assessment, project planning and implementation, and monitoring and evaluation, is necessary for translating research into practice (Piñeiro et al., 2020). Technical assistance providers include the NRCS, conservation districts, Cooperative Extension, and agricultural professionals such as Certified Crop or Pest Control Advisors. Technical assistance materials include videos, factsheets, and decision-support toolkits, like those available through the NRCS, Soil Health Nexus, and state soil health initiatives. Resources frequently feature growers who successfully adopted a conservation practice, with accompanying "why and how" materials. Technical support can also be tailored to specific growers or communities. The NRCS provides individualized carbon and conservation plans, whereas Utah Soil Health Program Specialists provide in-field assessments. "Train the trainer" programs like the Washington Conservation Commission's Center for Technical Development can also provide additional education for existing practitioners. Most importantly, grower peer-to-peer networks including virtual forums, field days, grange hall meetings, and commodity conferences, are an effective provider of technical assistance. It is well established that other growers are a primary source of information for growers (Sutherland and Marchand, 2021). As such, peer-to-peer networks have been formalized by groups such as the National Association of Conservation Districts' Soil Health Champions Network, or through the Ohio Soil Health Initiative's Soil Health Ambassador Program.

### 4.6.1. Strengths

Technical assistance providers lower the barriers to entry for growers to practice conservation by filling knowledge gaps, aggregating relevant resources, and working through place-based challenges such as climate or access to resources (Piñeiro et al., 2020). Furthermore, growers better connected to early adopters are more likely to adopt conservation practices themselves. The mere presence of an early adopter in a given region can increase an entire community's access to infrastructure, equipment, and knowledge (Carlisle, 2016).

### 4.6.2. Limitations

Technical assistance infrastructure can be time- and cost-intensive to establish and maintain, as it requires professional expertise, ongoing education, and community relationships established across time (Norton and Alwang, 2020).

### 4.6.3. Opportunities

Because technical assistance is essential for the success of all other strategies for building and protecting soil carbon, increasing technical assistance availability should be prioritized in all policies and programs. Increased funding and resources should be dedicated to continually training, employing, and equipping technical assistance providers and farmer support networks (Wick et al., 2019). These practitioners would ideally provide generalized toolkits, site-specific consultation, and foster peer-to-peer knowledge exchange, while working to develop long-term relationships built on trust.

## 4.7. Certification programs

One market-based strategy for promoting soil carbon sequestration adopts the "market segregation" approach, in which crops grown with specific practices are segregated from "business as usual" crops to create– or ensure access to– a market, or to elicit a higher price. The most high profile example is the certified organic program, in which consumers frequently pay a premium for crops grown without synthetic pesticides and fertilizers (Thøgersen et al., 2019). This model is increasingly employed for other farming practices, including those that protect wildlife or employ socially just labor practices. Certification schemes allow growers access to branding materials (e.g., signs and labels, or blockchain technology and smart tagging; Motta et al., 2020; Van Wassenaer et al., 2021) which help them negotiate higher prices with supply chain partners or directly with consumers. Examples with soil-specific components include the Michigan Agriculture Environmental Assurance Program (MAEAP) or Saving Tomorrow's Agricultural Resources (STAR). Under these schemes, growers voluntarily provide information about practices such as the frequency of their tillage and soil testing, the source of their fertility, or how they manage crop residues. Responses are algorithmically converted into scores, and farms above a certain threshold can participate in branding initiatives with slogans such as "Environmentally Verified." In the STAR program, the certification scheme is combined with an incentive program in which supply chain partners can provide per acre payments to growers with higher scores.

### 4.7.1. Strengths

Certification programs can improve the business case for soil health and soil carbon sequestration by generating market valuation for conservation practices. This is likely to lead to more sustained behavior change than incentive payments alone, as economic reward is continuous. A successful certification scheme can reward early adopters, improve farm profitability, allow industry partners to work towards sustainability goals, and provide an avenue for governmental or public interest groups to publicly recognize growers and conduct soil outreach and education.

### 4.7.2. Limitations

Certification programs can be resource-intensive to operate and are frequently supported by grant funding. Additionally, the popularity of this approach can lead to "certification fatigue," in which growers choose not to enroll because of the multitude of options available, and the administrative resources required to participate (Stephenson et al., 2022). Like incentive programs, most contemporary certification programs reward the implementation of practices rather than the delivery of outcomes. Because conservation practices do not uniformly lead to soil carbon increases in all contexts, the outcome of increased soil carbon storage is not guaranteed.

### 4.7.3. Opportunities

Certifications should be paired with incentive programs, as in the case of STAR. An incentive or cost share payment can help initiate conservation, while market-based approaches can help sustain it. To generate a broadly recognized market signal and to minimize certification fatigue, programs could be scaled while remaining regionally customizable. As with incentives, certifications would ideally incorporate research partners to increase understanding of whether conservation practices are having the desired effect.

## 4.8. Agricultural finance tools

There is increasing recognition that agricultural finance institutions are impacted by—and have a role to play in mitigating—the effects of climate change (World Bank Group, 2016; Gauthier et al., 2022). This is especially timely as climate change increases uncertainty for farmers, and makes risk reduction and financing tools more essential than ever. Despite the necessity of these tools, however, access to capital remains one of the largest barriers farmers face when implementing conservation practices (Ranjan et al., 2019).

### 4.8.1. Strengths

To respond to these challenges, several innovative financial products have emerged that incentivize long-term stewardship rather than maximum yields. For example, revolving loan programs offer growers low interest long-term loans to access the capital required to implement conservation practices. Examples include Mad Capital and the AGRI3 Fund, a public-private partnership between the United Nations Environment Programme and Rabobank. Climate-smart tax credits can also be made available, as in Pennsylvania where the Resource Enhancement and Protection Program provides state tax credits to producers to implement conservation practices. Crop insurance reform is also underway, as current policies can disincentivize experimenting with new practices (Annan and Schlenker, 2015) or preclude practices such as cover cropping, crop intensification, or crop diversification (Natural Resources Defense Council, 2017). The USDA's Pandemic Cover Crop Program (PCCP) was recently piloted to reduce insurance premiums by $5 per acre for participating growers that planted cover crops.

### 4.8.2. Limitations

The climate crisis is in large part due to market-driven resource consumption and growth imperatives (Cook et al., 2016). Incentivizing and valuing conservation practices within this system may hinder wider systemic reform efforts.

### 4.8.3. Opportunities

Within the current system, climate-smart financial tools and crop insurance programs are essential components to optimizing the climate change mitigation and adaptation potential of agricultural lands. As such, financial institutions, governmental agencies, and NGOs must continue working towards reform. Recommendations from advocacy groups such as the American Farmland Trust and Natural Resources Defense Council include eliminating fallow requirements, phasing out single-crop, yield-based coverage in lieu of whole farm revenue protection, destigmatizing the use of cover crops as a risky practice, and incentivizing the use of best management practices through insurance premium reductions (Natural Resources Defense Council, 2017; Beckie et al., 2019; van der Pol et al., 2021). USDA PCCP funding should be made permanent and expanded to include additional conservation practices, while climate-smart tax credit programs could be also expanded to a federal level. Agricultural finance tools are intended to provide a safety net for growers. This must increasingly include support for climate change adaptation.

## 4.9. Public outreach and education campaigns

Contemporary soil documentaries, books, websites, campaigns, and conferences are numerous (Amundson, 2022). For example, Chefs for Healthy Soil works through culinary communities to educate eaters about the importance of soil conservation. Soil Your Undies raises awareness about soil biodiversity and the role of soil microbes. Soil Life illustrates basic soil science concepts with simple and beautiful graphics.

### 4.9.1. Strengths

Public enthusiasm for soil carbon and soil health has been instrumental in garnering the political momentum necessary to allocate funds to diverse policies and programs. This illustrates how vital public outreach and education is to all other strategies for increasing soil carbon.

### 4.9.2. Limitations

The nuanced role of soils in climate change mitigation does not easily lend itself to slogans and sound bites. As such, catchy public interest campaigns run the risk of oversimplifying the science, overpromising the potential, and creating confusion in what is possible or practical to achieve.

### 4.9.3. Opportunities

Outreach and education can sustain political interest, generate market valuation, and clarify sources of confusion in soil carbon science. Successful campaigns should aim to accomplish all three.

## 4.10. Regulation and mandatory compliance

To our knowledge, there are no programs which regulate the formation and preservation of agricultural soil carbon via mandatory compliance. New Zealand may eventually regulate agricultural GHG emissions, though rules are currently limited to a GHG reporting requirement until emission reductions are more economically and technically viable (Prokopy et al., 2015). Other aspects of soil management are regulated in some regions in the US, including the quantity and timing of nitrogen-based fertilizers or the application of manure, the use of fumigants to treat soilborne disease, or tillage activities via air quality particulate matter thresholds. A small minority of growers may be subject to contractual soil carbon obligations if enrolled in voluntary carbon markets, or through corporate supply chain purchasing agreements.

### 4.10.1. Limitations and opportunities

Soil carbon is not easily integrated into regulatory and contractual frameworks, as previously discussed in the context of carbon markets. As such, the continued administration of voluntary rather than mandatory programs is appropriate, as well as the development of farm-specific recommendations rather than one-size-fits-all prescriptions.

# 5. Opportunities for increasing soil carbon storage

What emerges from a detailed review of strategies for building and preserving soil carbon is that a sound approach should drive innovation, engage stakeholders, address structural issues and lower barriers to adoption, increase market valuation, be system-specific, not place undue burden on producers, provide near-term benefits *and* lasting change, promote co-benefits, and minimize externalities. Given this extensive list, it is clear that no one strategy is sufficient. Table 1 qualitatively illustrates how diverse approaches are required to achieve these goals, while Figure 3 illustrates how diverse stakeholders are also required.

We draw from the extensive scientific literature on soil carbon, and the strengths and limitations of current US approaches, to conclude by recommending that the below principles guide the creation of all future US policies and programs:

1. **Natural climate solutions are only part of the solution.** Climate change mitigation requires multiple strategies, including reducing current emissions (e.g., using less fertilizer per unit of production or driving a more fuel-efficient tractor), technological measures (e.g., geologic carbon capture and storage), *and* land management optimized for soil and vegetative carbon sequestration. Increased soil carbon cannot pick up the check for other emission sources, and will not solve the climate crisis in isolation.
2. **Climate change adaptation must be prioritized alongside climate change mitigation.** An exclusive policy focus on soil carbon for climate change mitigation misses opportunities to

**TABLE 1** Current United States strategies to building and preserving soil carbon, and their potential contributions to an effective, science-informed policy and program portfolio. This qualitative figure illustrates how diverse approaches are required to achieve multiple goals.

| | Supports practice adoption | Drives innovation | Generates economic valuation | System-specific | Not a burden to producers | Rewards early adopters | Provides near-term results | Leads to lasting change | Promotes co-benefits | Minimizes externalities | Obligates action |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Incentive payments | ✓ | ✓ | | | | | ✓ | | ✓ | | |
| Carbon markets | ✓ | ✓ | ✓ | | | | ✓ | | | | ✓ |
| Research | ✓ | ✓ | | ✓ | | | | ✓ | ✓ | ✓ | |
| Modeling efforts | ✓ | ✓ | | | | | | | | | |
| Technical assistance | ✓ | ✓ | | ✓ | ✓ | | ✓ | ✓ | ✓ | ✓ | |
| Peer to peer networks | ✓ | ✓ | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | |
| Certification programs | ✓ | | ✓ | ✓ | | ✓ | ✓ | ✓ | ✓ | | ✓ |
| Finance tools | ✓ | ✓ | ✓ | | | | ✓ | | ✓ | | |
| Public outreach | ✓ | ✓ | ✓ | | ✓ | ✓ | | ✓ | ✓ | | |
| Regulation | ✓ | | | | | | ✓ | | | | ✓ |



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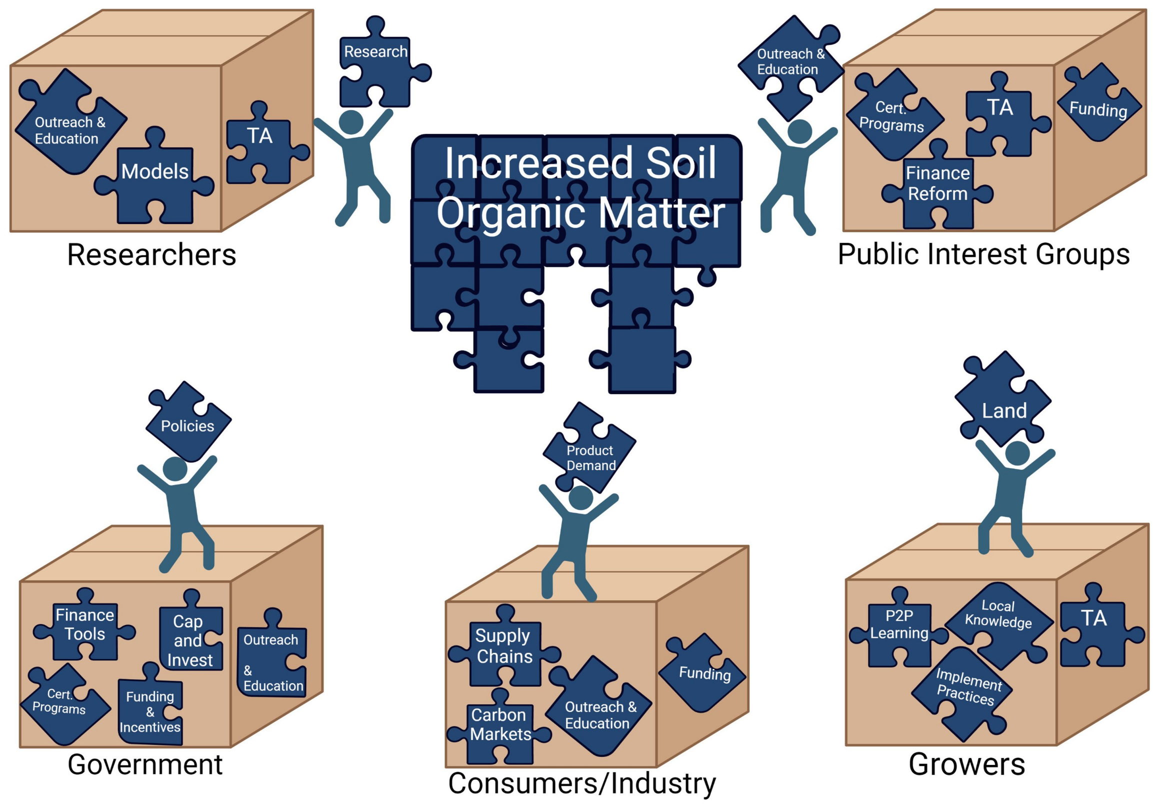


FIGURE 3
Conceptual diagram illustrating how diverse stakeholders contain the varied expertise required for the creation of an effective, science-informed policy and program portfolio in the United States.

promote SOM co-benefits, and therefore climate adaptation and resilience. Policies and programs should protect soil and improve soil management, independent of the direct impact on carbon.

3. **The science of soil carbon measurement is not yet sufficiently advanced to be responsibly integrated in the contractual frameworks proposed in cap-and-trade or regulatory schemes.** Soil carbon formation and storage is complex, heterogenous, dynamic, and the science and technology are rapidly evolving. Measuring and modeling strategies must become more accurate, cost-effective, and scalable to be readily implemented.
4. **Practice- and place-specific programs must be administered in lieu of one-size-fits-all prescriptions.** The carbon sequestration potential of soil depends on a multitude of variables. Site specific programs are most likely to lead to science-informed recommendations, maximize the impact of conservation practices, minimize barriers to adoption, and avoid externalities.
5. **Structural issues and barriers to adoption must be addressed as part of all programs and policies.** This includes gaps in site- and practice-specific knowledge, lack of access to resources, lack of economic valuation for soil conservation, and inequities in how programs reach socially disadvantaged farmers. Significant investment in research, market development, technical assistance, outreach and education, and stakeholder engagement is required.
6. **Effective and equitable soil carbon programs and policies require the collaboration of diverse stakeholders.** Policymakers, governmental agencies, universities, growers, industry groups, public interest groups, environmental nonprofits and NGOs, consumers, and community members each have unique contributions to make to defensible, science-informed, and user-driven programs. All entities should be engaged early and often. Furthermore, collaboration between federal, state, and regional groups can lead to pooled resources and amplified impact.
7. **Careful planning and investigation can minimize externalities.** Environmental improvements should not be made at the expense of frontline communities, nor should a regional intervention have negative impacts elsewhere (e.g., reduced global crop yields, or reduced GHGs in one place in exchange for increased emissions elsewhere). Pollution trading, or exchanging one externality for another, should be carefully considered during the planning process of any policy or program.

Finally, and perhaps most importantly, is that **the challenges in building and measuring soil carbon should not dissuade action**. Soils are the foundation of our agricultural and social systems. The wholesale protection of soils and improvement of soil management is required to promote ecosystem services such as carbon sequestration, air and water filtration, crop production, and biodiversity support. The current popular and political momentum must be harnessed to address climate change, and to protect this invaluable terrestrial resource. Through collaboration, careful planning, and the acknowledgement that soil carbon storage is complex and nuanced, soils can remain a vital tool in working towards a more sustainable future.

## Author contributions

DG wrote the first draft of the manuscript and designed Table 1. DR designed the Figures 1–3. All authors contributed equally to the conception of this manuscript, revising the manuscript, table, and figures, and approved the final 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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# Paving the way to net-zero: identifying environmental sustainability factors for business model innovation through carbon disclosure project data

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Net-zero emission targets are crucial, given the environmental impact of the food and beverage industries. Our study proposes an environmentally focused Sustainable Business Model (SBM) using data from 252 food, beverage, and tobacco companies that reported to the Carbon Disclosure Project (CDP). We investigated the risks, opportunities, business strategies, emission reduction initiatives, and supply chain interactions associated with climate change by analyzing their qualitative answers using the NVivo software. Following the grounded theory approach, we identified the Environmental Sustainability Factors (ESFs) that support businesses in meeting pollution reduction targets. The ESFs were integrated with Osterwalder's business model canvas to create an archetype focused on delivering "net-zero" or "carbon neutral" value to customers. The model's efficacy is enhanced by the advantages and motivations of environmental collaborations. The paper provides critical support for sustainability theories and assists Small and Medium Enterprises (SMEs) to develop strategic business models for net-zero emission targets.

KEYWORDS

**Carbon Disclosure Project (CDP), net-zero emissions, food and beverage sector, sustainable food supply chains, environmental collaborations, Business Model Innovation (BMI), Sustainable Business Model (SBM)**

## 1. Introduction

Climate change disasters (floods, earthquakes, bushfires, hurricanes etc.) are not limited to highly polluting countries and the regulatory bodies and governments have now realized the global nature of this problem, and that the only solution is to reduce and eliminate Greenhouse Gas (GHG) emissions at a global scale. The latest developments in the sixth assessment report of the Intergovernmental Panel on Climate Change (IPCC) have also clarified the importance of limiting global heating to 1.5°C above pre-industrial levels (Pörtner et al., 2022). To avoid major climate catastrophes, human-caused emissions must fall to half of the 2010 levels by 2030 and to net zero by 2050 (Salas et al., 2020). The Paris Agreement acts as a landmark in this regard, as 196 nations established an objective of net-zero emissions by the year 2050.

Businesses play a crucial role in achieving these global targets. Not only governments and shareholders, but customers also push the companies to develop net-zero targets in line with the Paris Agreement and IPCC reports. To achieve carbon neutrality goals, businesses need to reduce emissions from all sources to as close to zero as possible—material sourcing, transportation, operations, energy consumption, and buildings and infrastructure. Any remaining emissions must also be balanced by capturing $CO_2$ emissions from the atmosphere through reforestation, peat and moss plantations, and the installation of Carbon Capture Technologies (CCTs) (Salas et al., 2020). A thorough understanding and analysis of three scopes of business emissions is critical in this regard: scope 1 refers to the direct emissions from on-site operations; scope 2 refers to the emissions from on-site energy usage; scope 3 includes all other indirect emissions from upstream and downstream supply chains (Luo and Tang, 2014). Among other sectors, food supply chains are considered highly emission-intensive, accounting for 35% of global GHG emissions mostly associated with cattle farming and land usage (Costa et al., 2022).

Environmental management of food supply chains is distinguished from other industrial supply chains because of the unique characteristics of food items including perishability, hygiene level, food contamination, and nutrition management. Many researchers and engineers have optimized the food supply chains in the context of sustainability, but a major challenge for researchers and industrialists is to achieve an ideal supply chain solution (Hammami and Frein, 2014). By ideal supply chain, we mean the one that leads to net-zero emissions of a product or company. Considering the challenges food supply chains pose to climate targets, researchers have started developing frameworks and models for food companies to reach carbon neutrality by 2050. However, there is a clear research gap when it comes to the development of an environmentally sustainable business model that delivers a net-zero value proposition. In this regard, a generic sustainable business model derived from benchmark food companies is critical to motivating both large and small enterprises to play their role in meeting global net zero emission targets.

Traditional business model canvas (Osterwalder and Pigneur, 2010) must be exploited across all its 9 constructs (customer value proposition, customer segments, customer relationships, channels, key activities, key resources, key partnerships, cost structure, and revenue streams) to optimize their interdependences in delivering net zero value proposition to the customer. Sustainable business models have emerged drastically, driving businesses to influence social and environmental sustainability standards. In this context, a Sustainable Business Model (SBM) is defined as an extension of the traditional business model with additional sustainability components, promoting the creation, capture, and delivery of ecological, social, and economic value (Bocken et al., 2014). An ecological or environmental value proposition is critical considering the latest developments (international environmental law, convention on biological diversity, Kyoto Protocol, Paris Agreement, UN SDGs) and businesses are looking for net-zero/carbon-neutral business models to meet their environmental regulations.

Our study intends to develop a sustainable business model with a net-zero value proposition by using the enterprise climate change data reported to Carbon Disclosure Project (CDP) in 2020. The CDP is a non-profit organization that runs the global disclosure system for companies, cities, states, and regions to administer their environmental impacts (Chen et al., 2021). Also, it employs an essential role in regulatory systems, driving companies to conform to global environmental standards (Depoers et al., 2016; Chen et al., 2021). Companies report to CDP to reflect their vision and efforts toward achieving Sustainable Development Goals (SDGs) and carbon neutrality targets. CDP has also become a vital platform for food manufacturers to showcase their efforts in reducing emissions across their supply chains. Moreover, a company can gain a competitive edge by disclosing to CDP and positioning itself as a leading environmentally conscious company (Depoers et al., 2016).

CDP categorizes the survey to obtain information across all scopes of emissions, i.e., scope 1, scope 2, and scope 3 emissions. The GHG Protocol requires reporting of Scope 1 and 2, while scope 3 is highly recommended but not compulsory (Ismail et al., 2021). However, our paper focuses on analyzing and interpreting the scope 3 related disclosure as it accounts for 90% of overall supply chain emissions. Managing scope 3 emissions is extremely critical to systematically achieving environmental goals. Therefore, we analyze enterprise disclosures of climate change-related risks and opportunities, emission reduction initiatives, business strategy, and value chain engagements to identify important practices required under different constructs of Osterwalder's business model canvas to deliver a net zero value proposition. This analysis will enable the development of a benchmarked SBM.

To reach the outcomes of the study, the paper is structured as; Theoretical background on climate change reporting, sustainable business models, and food supply chain management is presented in Section 2, followed by data analysis and methodology (Section 3) to identify promising environmental sustainability factors in food supply chains. This leads to results and discussion (Section 4) which systematically reviews the key constructs of a sustainable business model, provides industrial and theoretical implications of the study, and presents an archetype sustainability model for food, beverage, and tobacco firms to set and achieve net-zero emission targets. Thereafter, limitations and future directions are presented in Section 5, followed by the conclusion in Section 6.

## 2. Literature review

The first commitment period of the Kyoto Protocol (2008-2012) aimed to reduce human-caused Greenhouse Gas (GHG) emissions to an average of 5.2% below 1990 levels (Howarth and Foxall, 2010). However, an exception was made regarding the adjustment of the 1990 baseline, which helped many developed nations to meet these targets (Maraseni and Reardon-Smith, 2019). In the second commitment period of the Kyoto Protocol (2012-2020), developed nations committed to reducing GHG emissions by 18% below the 1990 baseline within eight years. However, this commitment proposed the use of indirect market-based mechanisms such as International Emissions Trading, Clean Development Mechanism (CDM) and Joint Implementations to meet the reduction targets (Masson-Delmotte et al., 2021). Moreover, it also allowed the parties to carry forward their carbon credits from the first commitment, providing an advantage to many countries (Maraseni and Reardon-Smith, 2019). However, these exceptions and exclusions have faced criticism as they allowed developed countries to engage in greenwashing practices. These practices involve relocating their emission-intensive plants to non-regulated countries while benefiting from emission trading schemes and purchasing carbon credits. Nevertheless, the latest agreements at the 26th COP (Conference of Parties) and the sixth assessment report of IPCC (The Intergovernmental Panel on Climate Change) have mandated that governments and companies focus on the reduction, elimination, and capture of GHG emissions from a cross-border perspective (Pörtner et al., 2022).

With the background of emerging climate change regulations for businesses, we reviewed the literature on the importance of CDP climate change reporting, sustainable business models and empowering strategies, and strategic environmental management in food supply chains. This allowed us to grasp sufficient theoretical knowledge to rebuild a sustainable business model with a net-zero value proposition for food, beverage, and tobacco firms.

## 2.1. Climate change reporting

Ismail et al. (2021) pointed out three types of international disclosure initiatives widely recognized in the sustainability field, which reflect the environmental strategy of firms. They are the Global Reporting Initiative (GRI) guidelines, the Global Compact (GC) principles, and the Carbon Disclosure Project (CDP). These initiatives are guiding companies to take responsible behaviors. Among others, the CDP is a vital project that could trace the amount of carbon emission during production and operations. Normally, information disclosure mechanisms allow the stakeholders including investors, customers, auditors, regulators, and others to understand the company's sustainability state. Moreover, these disclosures play an essential role in regulatory developments, exerting pressure on companies to conform to social and environmental standards (Cormier et al., 2005; Depoers et al., 2016). This also impacts companies' market reputation and the legitimacy of their commitment to preventing pollution. Furthermore, by engaging in CDP information disclosures, companies can enhance their brand image and maintain a persistent position among leading environmentally sustainable firms (Depoers et al., 2016).

CDP collects information on climate change-related risks and opportunities identified and actioned by leading companies. They further classify the environmental risks and opportunities in accordance with the drivers which allows firms to trace emission-intensive sources of their business (CDP, 2019b). CDP also inquires how these risks and opportunities affect the business strategy, helping the firms to integrate environmental management into their organizational strategy (Herold and Lee, 2019). CDP disclosure highly emphasizes supply chain engagements and systems perspective as the key determinants for reducing scope 3 emissions of a firm (CDP, 2019a). Through the CDP information, businesses can identify their supply chain hotspots and develop management strategies for sustainable supply chains that encourage the reduction of these emissions (Herold and Lee, 2019).

Consequently, the CDP possesses the ability to influence emerging regulations and raise the importance of carbon capture within companies. The CDP claims that its findings benefit organizations and those that use this information because it provides a medium for companies to assess their GHG emissions against external or internal environmental policies (Jain et al., 2015). With this context in mind, CDP is a significant source of vital information that could be used by a wide span of professionals from academics and tutors to policymakers and investors (Blanco et al., 2016). Fagotto and Graham (2007) support this phenomenon and argue that with a transparent system in place, the CDP could be a key component in raising the power of public opinion in the industrial sectors. Therefore, using CDP data to develop comprehensive sector-specific sustainability models is a potential doorway to meeting global net-zero emission targets.

## 2.2. Sustainable business models

In the context of management theory, business models emerged for companies to attain competitive advantage by strategic integration of various business model components (McGrath, 2010). However, researchers and practitioners have begun to look beyond the conventional paradigm of value generation solely for customers and companies. Instead, they have embraced a broader perspective that includes the generation of value for the environment and society as well (Comin et al., 2019). With these changing trends, stakeholder involvement rapidly increased and businesses started appraising stakeholder theory to deliver value for their Investors, shareholders, suppliers, employees, and partners alongside the customers (Hörisch et al., 2014; Tolkamp et al., 2018). Most recent sustainable business models have fortified the concept of the circular economy (Lahti et al., 2018), technology and stakeholder-driven innovations (Baldassarre et al., 2017), environmental stewardship (Csutora et al., 2022), and supply chain collaborations and industrial symbiosis (Roome and Louche, 2016; Tolkamp et al., 2018).

Research on the incorporation of sustainability factors into business models is still in its infancy, and sector-based research, more specifically, exhibits a significant gap (Ritala et al., 2018). There is a lack of managerial understanding when it comes to the feasible application of sustainability practices in existing business models (Bocken et al., 2014). The fashion and apparel sector dominates the research on the business model innovation (Todeschini et al., 2017; Kozlowski et al., 2018), where innovations and stakeholder collaborations are found to be the critical drivers of a functional and sustainable business model. The study conducted by Yip and Bocken (2018) highlights digitalization and resource recovery as crucial elements for developing a sustainable business model in the banking Industry. Another services-oriented study (Høgevold et al., 2015) linked stakeholder engagement in reducing the environmental burden to the success of SBM in the hotel industry. A distinctive research article on sustainable business models for the most criticized sector, energy, implies the development of a stakeholder network to generate, capture, and deliver value for the customers, business, environment, and society (Rossignoli and Lionzo, 2018). Creating an effective network of stakeholders is critical in promoting awareness, education and practice, and a sense of responsibility in involved parties, and ultimately the society (Tolkamp et al., 2018).

Therefore, research in sector-specific SBMs is still novel with only limited studies leading to the development of sector-specific sustainable business models (Høgevold et al., 2015; Barth et al., 2017; Franceschelli et al., 2018; Kozlowski et al., 2018; Rossignoli and Lionzo, 2018; Yip and Bocken, 2018). However, none of these studies discussed the implications of net-zero value propositions on other components of the business model. Moreover, these studies have not used a broad set of real companies' data to demonstrate the applicability and operationalization of SBM. In today's business landscape, delivering an environmental value proposition is not only imperative from an ecological standpoint but also holds the potential to strengthen businesses' core competencies, dynamic capabilities, and competitive advantage.

### 2.3. Strategic environmental management in food supply chains

The food, beverage, and tobacco sector play a vital role in regional and global economies, contributing to Gross Domestic Product (GDP) growth because of the perpetual consumer demand it generates. The simultaneous growth in population and wealth demands more quantities and varieties of food, thereby intensifying market volatility while posing a threat to the limited natural resources of Earth (Zhu et al., 2018). Today, the major environmental sustainability issues in food supply chains include but are not limited to energy conservation, ecological deterioration, GHG emissions, and natural resource conservation leading to unprecedented effects of climate change and global warming.

Moreover, the stakeholder demand for transparency, food security, and food waste reduction has reached unprecedented levels and resultantly, food firms are pressurized to adopt environmentally sustainable business models. Therefore, government bodies, customers, and other stakeholders motivate the firms to develop sustainable business models centered around green practices such as eco-designing, green purchasing, green manufacturing, and green transportation. Such green practices facilitate the transition to a circular economy and contribute to global greenhouse gas emission reductions (Asif et al., 2020). Closed-loop Supply Chain (CLSC) models are also extremely popular in this regard (Guide and Van Wassenhove, 2009; Miemczyk et al., 2016) and extended CLSC models have included waste management and resource recovery activities as part of the loop to enable circular economy (Sgarbossa and Russo, 2017). Furthermore, the study conducted by Mondragon et al. (2011) has provided robust evidence to support the positive influence of supply chain integration level on both the reverse and forward components of a Closed-Loop Supply Chain (CLSC). Some recent researchers have worked on the potential integration of Blockchain Technology (BCT) in the supply chains as it can resolve many CLSC-related uncertainties including information discrepancies, transparency in environmental reporting, and emissions' data management (Saberi et al., 2019; Schmidt and Wagner, 2019; Asif and Gill, 2022; Asif et al., 2022).

However, the efficacy of strategic environmental initiatives and green practices depends on effective inter and intra-organizational collaborations (Asif et al., 2020). The existing literature challenges the conventional approach of simply pressuring suppliers to enhance their performance and places more emphasis on direct involvement in suppliers' operations to achieve environmental objectives (Nyaga et al., 2010; Chen et al., 2013). The buying firm must effectively maintain its supplier's performance and capabilities. Numerous researchers have employed systems theory to analyze the importance of collaborations among diverse actors within the food industry. Since its development by Bertalanffy (1968), systems theory has found extensive application in different research sectors including the food industry which is characterized by complex stakeholder interdependencies (Caswell et al., 1998; Menrad, 2004; Asif et al., 2020). Systems theory rejects the notion of isolation and asserts that a system can only be competitive if all its components and sub-systems are well aligned, integrated, and maintain robust relationships (Whitchurch and Constantine, 2009). Therefore, the systems concept serves as one of the theoretical bases for our research, as we seek to integrate green practices across various components of SBM and explore their complex relationships.

## 3. Data analysis and methodology

To find the Environmental Sustainability Factors (ESFs) relevant to each component of Osterwalder's business model canvas, we used thematic data analysis of 252 firms from the food, beverage, and tobacco sector who reported their data to CDP in 2020. This will help in reinventing the business model for food, beverage, and tobacco firms with the integration of ESFs into relevant components of their business model and aligning critical environmental aspects with their organizational strategy.

These ESFs hold value not only for large enterprises but also for SMEs as they account for more than 50% of global business-sector emissions (OECD, 2022). SMEs face the pressing concern of potential competitive disadvantages and missed low-carbon opportunities if their business models do not adapt to the latest shifts in climate change trends. In this context, CDP defines SMEs as non-subsidiary organizations with fewer than 500 employees, which aligns with the definition proposed by SME Climate Hub and Science-based Targets Initiative (Project, 2021). CDP encourages SMEs to engage in CDP climate change reporting under the modules of energy, value chain emissions, management and resilience, and climate solutions.

Therefore, it is crucial for SMEs to determine the ESFs relevant to their business, integrate them into their business models, report the progress to CDP, and contribute toward global net-zero emission targets. The ESF-integrated business models will be useful for all members of food supply chains willing to rejuvenate their business strategy in current climate change uncertainties. In this regard, continuous situation analysis is critical to businesses' competitiveness and survival as argued in the literature—businesses need to be proactive in reinventing or changing their business model on sensing any change in the external environment (Jolink and Niesten, 2015).

For analysis purposes, we adopted the well-famous six-step thematic analysis method proposed by Braun and Clarke (2012). Their method provides flexibility to authors dealing with complex qualitative data to move across the steps and make changes as

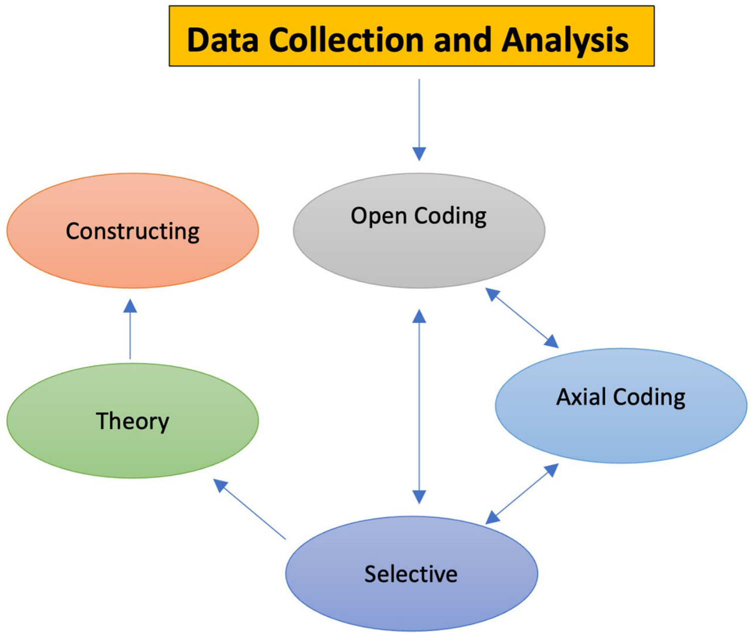


FIGURE 1
Coding methods in qualitative analysis (Source: Williams and Moser, 2019).

deemed appropriate. To keep the analysis compact, we merged step 4 (reviewing themes) and step 5 (naming themes) and skipped the description of step 6 which is about writing the report. In steps 3 and 4 of the data analysis, we also implemented the qualitative analysis process proposed by Williams and Moser (2019). They suggested a three-step coding method including open coding, axial coding, and selective coding to develop a meaningful case from the analytical findings. As we tend to develop an environmentally sustainable business model case, this approach was very relevant and useful in finalizing the ESFs that ensure the success of an SBM from an environmental perspective. The three-step coding process is shown in Figure 1 where cyclic/continuous comparison among three stages of coding leads to a new theory or case.

## 3.1. Step 1; become familiar with the data

Authors of this paper have extensively worked on CDP data in their previous research where they benchmarked the best companies to develop a generic framework for scope 3 emission evaluations in the food supply chains (Asif et al., 2022). Now, the authors extend their research using insightful CDP data to develop a sustainable business model applicable to the global food sector. Authors have gone through the relevant literature and existing sustainable business models to identify the research gaps that can be filled using CDP data i.e., a proof-based business model that achieves the environmental sustainability goals of food-related firms. For this paper, we focus on the CDP data reported under categories of risks and opportunities, business strategy, emissions reduction initiatives, and supply chain engagements. These categories were selected based on their relevance to the development of a new business model. For instance, cross-sectional analysis of risks and opportunities and business strategy helps in the identification of strategic environmental priorities, and data on emission reduction initiatives and supply chain engagements help in understanding key practices and approaches for the development of a collaboration-oriented business model.

Moreover, we probed into the initiatives taken by successful companies to mitigate carbon footprints and not only survived in the market but still are top-rated food, beverage, and tobacco brands. We selected different questions mentioned in Appendix 1 and aligned them in a sequence that supports our research. We also shortlisted the top-performing companies to analyze their methodology for reaching net-zero emission targets. These accountability measures enabled us to concise the required data and become familiar with ongoing approaches companies are using to propose, create, deliver, and capture environmental value through their SBMs.

## 3.2. Step 2: generating initial codes

This stage is critical as we need to organize the data in a meaningful and systematic way. We used a bottom-up also called an inductive approach for data coding as we intend to identify ESFs for a new business model related to food firms. This approach allows the researcher to code and interpret the existing data to develop new theories and models also known as the approach of grounded theory (Braun and Clarke, 2006).

For generating specific codes, we used NVIVO software as it helps to accomplish the qualitative analysis more systematically.

TABLE 1 Supply chain engagements and their types.

| Engagement partners | Engagement type | Frequency |
|---|---|---|
| Suppliers | Compliance and onboarding | 35 |
| | Incentivization | 44 |
| | Information collection | 68 |
| | Innovation and collaboration | 31 |
| Customers | Information sharing | 59 |
| | Innovation and collaboration | 35 |
| Beyond value chain | Engagement with policy makers | 53 |
| | Funding research organizations | 28 |
| | Engagement with trade associations | 119 |

TABLE 2 Initial themes based on open-coding approach.

| Initial thematic domains | |
|---|---|
| Eco-friendly commitments | Intellectual resources |
| Regular questionnaires | Emotional resources |
| Green supply chain | Virtual stores |
| Industrial symbiosis | Fuel efficiency |
| Online retailing | Sustainable cultivational practices |
| Awareness campaigns | Consumer changing trends |
| Returnable products | Carbon positive products |
| Sustainable selling growth | Regenerative practices |
| Certification programs | Biodegradable materials |
| Published reports | Managing tradeoffs |
| Sustainable crop yielding | One way packaging |
| Organic production | Green capital investments |
| Green agricultural suppliers | Revolutionary demands |
| Reduced operational cost | Interactive packaging design |
| Promoting biodiversity | Incentivization |
| Green packaging | Sustainable material Sourcing |
| Shifting trends | Renewable packaging |
| collaborative transport | Fuel tax |
| Carbon tax | Technological commitments |
| Sustainability innovations | Environmental risk management |
| Green workforce | Inhouse energy efficiency |
| Joint certification programs | Marketing sustainability |

At first, we set up the data in accordance with climate change-related risk and opportunity drivers as mentioned in the CDP report. Companies endorsing the risk and opportunity drivers were shortlisted and high-frequency drivers were analyzed for the corresponding descriptive responses from the companies. Analysis of descriptive responses helped us identify the codes relevant to achieving net-zero targets. For instance, shift in consumer preference is a reputational risk driver and its descriptive analysis helped in generating codes relevant to changing patterns in food consumption and demand.

Similarly, we analyzed the responses of 252 companies related to their supply chain engagements. Engagements with suppliers, customers, and beyond the value chain were critical in this regard. Table 1 demonstrates engagement types identified from the CDP report:

Around 100 companies did not mention any engagement with their suppliers, neither in terms of the type of engagement nor the plans for engagement. This is alarming as supplier engagement is one of the critical elements in addressing climate change-related risks and opportunities (Colicchia et al., 2018). Out of 152 companies that responded "yes" to engagement with suppliers, 122 companies disclosed their information on supplier engagement and their type of engagement was analyzed from qualitative responses to generate the codes.

A total of 625 codes were generated from CDP data through the analysis of open-ended questions. Repetitive and same meaning codes were scrutinized and finally, 150 codes were shortlisted. All the selected codes were either practices, initiatives, tactics, or other strategies that the food, beverage, and tobacco firms have used to improve their environmental performance. Highly repeated codes were considered critical and explicitly discussed under the "Results and Discussion" section. A list of 150 selected codes and their frequency is presented in Appendix 2.

## 3.3. Step 3; searching for themes

At this stage, we clumped the identical and correlated codes under specific themes. We followed the open coding approach during this step as it aims at forming "concepts" from analyzed data or phenomena, also named as a concept-indicator model. Using a continual comparison of recorded codes, a concept-indicator model allows emergence of themes as an indicator of a concept (Saldaña, 2021). Essentially, open coding allows the researcher to examine through company responses and organize similar textual data i.e., concept indicators, in high-level initial thematic domains (Williams and Moser, 2019) as shown in Table 2.

## 3.4. Step 4 and 5; reviewing and naming themes

Following Williams and Moser (2019) qualitative analysis framework, we applied axial and selective coding approach at this stage. While open coding helps to identify emergent themes, axial coding allows for further refinement, alignment, and categorization of thematic domains. Final themes (axial codes or core codes) emerged as aggregates of closely inter-related themes with strong supporting evidence. A constant comparison method was adopted to organize and refine the activities. The focus was to compare companies' responses, emerging themes, and relevant codes continually to develop new thematic categories also called as ESFs for further analysis during "selective coding."

TABLE 3 Business model components, related Environmental Sustainability Factors (ESFs) and included best practices.

| Component of SBM | Environmental sustainability factors (Themes) | Green practices, initiatives, and programs from CDP data analysis (Codes) |
|---|---|---|
| Channels | Fuel efficiency | • Systematic use of fuel and energy<br>• Replacing non-renewable fuels<br>• Switching fuels<br>• Optimizing transportation routes<br>• Avoiding empty fleet runs<br>• Electric vehicles<br>• Energy saving schemes |
| | Collaborative transport | • Flexible Routes<br>• Joint Transport With Committed Partners<br>• Ensuring Sustainable Logistics<br>• Offering Container Space To Others<br>• Avoiding Empty Fleet Runs<br>• Innovation In Transportation<br>• Joint Driver Training Programs<br>• Collaborative Transportation Management (CTM) |
| | Virtual stores | • E-commerce marketing<br>• Webstores<br>• Sharing platforms<br>• Energy saving<br>• Collaborative production and sales |
| | Sustainable storage | • Low emitting refrigerant gases<br>• Consolidate storage<br>• Sensors and actuators for data recording<br>• Protecting high carbon stock areas<br>• Smart refrigeration process |
| Cost structure | Cost of sustainable operations | • Cost of energy usage<br>• Sustainable operational costs<br>• Sustainable production costs<br>• Sustainable supplier selection costs<br>• Process optimization costs<br>• Reverse logistics costs<br>• Effective capacity planning<br>• Sustainable supply chains |
| | Revolutionary demands | • Expanding clean energy generation<br>• Responding to government regulations<br>• Developing zero waste economy<br>• Embracing emerging regulations<br>• Green capital investments |
| | Carbon related tax | • Carbon tax<br>• Legal compliances<br>• Energy tax<br>• Fuel tax |
| | Environmental risk management | • Severe weather (flood, hurricane, earthquake) risks<br>• Deforestation risks<br>• Lack of pollution limits<br>• Air pollution risks<br>• Acute physical risks<br>• Regulatory risks |
| Customer relationships | Awareness campaigns | • Apprise customers about carbon emissions<br>• Marketing sustainability achievements<br>• Customer involvement in designing<br>• Customer education<br>• Packaging refund schemes<br>• Incentivizing conscious customers<br>• Innovation campaigns |
| | Promoting biodiversity | • Protecting forests<br>• Biodiversity management<br>• Carbon farming<br>• Healthy soil<br>• Sustainable agriculture<br>• Changing weather patterns |
| | Carbon positive products | • Using raw materials with low carbon impact<br>• Manufacturing products with low carbon impact<br>• Reducing, reusing, and recycling approaches |

*(Continued)*

TABLE 3 (Continued)

| Component of SBM | Environmental sustainability factors (Themes) | Green practices, initiatives, and programs from CDP data analysis (Codes) |
|---|---|---|
| | Eco-friendly commitments | • Engagement with sustainable firms<br>• Engagement with resource-efficient countries<br>• Direct relationship with trade associations<br>• Increasing transparency in GHG emissions with suppliers<br>• Restricting food wastage during production |
| Customer segments | Consumer changing trends | • Shifting consumer trends<br>• Knowledge sharing<br>• Increasing demand for organic products<br>• Willing to pay an extra price for sustainability |
| | Interactive packaging design | • Making recycling labels<br>• Symbolizing recycling procedure<br>• Printing awareness stories<br>• Motivational games on sustainability |
| | Marketing sustainability | • Promotional campaigns<br>• Offering carbon tokens to customers<br>• Sustainability branding |
| Key activities | Regenerative practices | • Practicing recycled raw materials<br>• Reforestation<br>• Sustainable livestock feed<br>• Crop rotation<br>• Design for reuse |
| | Green packaging | • Reusable packaging<br>• Packaging from recycled material<br>• Multiple use plastic<br>• Non-plastic alternatives<br>• Compostable packaging<br>• Reduced packaging material<br>• Incentivizing package returns<br>• Use of bioplastics |
| | Organic production | • Sustainable agriculture<br>• Biodiversity considerations<br>• Substitutional additives<br>• Weed management<br>• Soil health management<br>• Fertilizer management<br>• Reduced tillage<br>• Reduced artificial fertilizers |
| | Inhouse energy efficiency | • Using LED lights<br>• Energy efficient production<br>• Using compressed air<br>• Use of solar PV<br>• Hydropower plants<br>• Inhouse energy generation<br>• Fossil free production<br>• Replacing chillers for sustainable refrigerant gases<br>• Switch from paper to e-communications |
| | Technological commitments | • Clean production technologies<br>• Sensor and actuator technologies<br>• Installing advanced/smart plants<br>• Information sharing through a blockchain platform<br>• Using intelligent sensors for farming<br>• Using blockchain technology for traceability<br>• Smart refrigeration process |
| Key partnerships | Industrial symbiosis | • Sharing waste<br>• Collaborative carbon capturing initiatives<br>• Sourcing recycled raw materials<br>• Carbon asset trading, emission trading system<br>• Collaborative LCAs |
| | Incentivization | • Incentive to growers/suppliers<br>• Incentive to contractors<br>• Transforming suppliers into partners<br>• Emission trading schemes |

*(Continued)*

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TABLE 3 (Continued)

| Component of SBM | Environmental sustainability factors (Themes) | Green practices, initiatives, and programs from CDP data analysis (Codes) |
|---|---|---|
| | Sustainable agricultural suppliers | • Trained farmers and suppliers<br>• Weed management assessment<br>• Integrated pest management<br>• Livestock feed management<br>• Crop rotation<br>• Manuring and composting<br>• Biological pest control |
| | Joint certification programs | • Environmental certification (ISO-14001 or climate active)<br>• Decarbonization certification programs<br>• Supplier certifications<br>• 3rd party sustainability certifications<br>• Request suppliers to answer CDP questionnaire |
| | Regular questionnaires | • Mandatory carbon reporting<br>• Pest control assessment<br>• Assessment of regular growers<br>• Cooperation with raw material suppliers |
| | Green supply chain | • Eco-design<br>• Green purchasing<br>• Green manufacturing<br>• Green transportation<br>• Reverse logistics<br>• Closed loop supply chain<br>• Circular economy<br>• Green supplier development<br>• Pollution halo effect<br>• Increase transparency in GHG emissions with suppliers |
| Key resources | Sustainability reports | • Sustainability information collection<br>• Sustainable business model<br>• GHG reporting to independent bodies<br>• Reputational risks<br>• Identification of climate risks<br>• Pest control reports<br>• ESG and CSR reports<br>• Environmental audit reports<br>• Distributing sustainability reports |
| | Renewable resources | • Use of primary fibers<br>• Regular paper recycling<br>• Plant-able or edible packaging material<br>• Elimination of single use crockery<br>• Renewable energy consumption |
| | Sustainable material sourcing | • Buying recycled raw materials<br>• Sustainable supplier selection<br>• Collaborative compost production |
| | Sustainability innovations | • Process automation<br>• Embedded systems<br>• Big data technologies<br>• Machine learning and artificial intelligence<br>• Managing innovation spillovers |
| | Green workforce | • Employee empowerment<br>• Employee involvement in sustainability decisions<br>• Embedded environmental training programs<br>• Sponsoring external trainings and certifications<br>• Awareness of emergency procedures and responses |
| Revenue stream | Sustainability incentives | • Tax credit<br>• Enhanced reputation<br>• Electric vehicle incentives<br>• Innovation grants<br>• First-mover advantages<br>• Emission reduction credits |
| | Tradeoff management | • Quality or cost of raw materials<br>• Transport emissions or costs for acquiring green vehicles<br>• High-efficiency technologies or cost savings<br>• Price adjustments |

*(Continued)*

TABLE 3 (Continued)

| Component of SBM | Environmental sustainability factors (Themes) | Green practices, initiatives, and programs from CDP data analysis (Codes) |
|---|---|---|
| | Selling growth | • Communication with customers<br>• Using social media<br>• Data visualization<br>• Realize superior customer value at the lowest possible cost |
| | Cost savings | • Natural resource reliance<br>• Trained labor on plant<br>• Cashing customer satisfaction |

As mentioned by Flick (2022), selective coding or third-level coding follows axial coding at a higher level of abstraction that leads to story development. For a story or case (environmentally sustainable business model) to emerge from data categories, further refinement of data, selection of final thematic categories, and systematically aligning selective themes with constructs of business model canvas were critical. Therefore, selective coding can fuel expression and facilitate the construction of meaningful outcomes or a theory from qualitative data (Williams and Moser, 2019).

Following the three-step coding process (open, axial, and selective coding), we reached the best green practices, environmental initiatives, and sustainable methods that align with eight constructs of the business model canvas, while the ninth construct of "value proposition" is centralized at "net-zero" or "carbon neutral" value proposition for a product or service. The alignment of selective themes with the eight components of business model canvas is demonstrated in Table 3.

All the themes or ESFs mentioned above depict the solution to the modern problem of environmental depletion and degradation. In the business models, companies can adopt a set of ESFs that best suit their organizational structure, supply chain, and profitability. For selected ESFs, businesses can determine relevant green practices, initiatives, or programs adopted by best-performing food companies from Table 3. It is important to note that every food firm has a similar but distinct business strategy and some of the SMEs are not ready to fully immerse themselves in SBM. Therefore, our provided framework gives the flexibility to select low-cost ESFs to begin with and take a gradual approach toward the development of a fully sustainable business model.

# 4. Results and discussion

As we discuss and align the generated themes (Environmental Sustainability Factors) with the components of a sustainable business model, we highly emphasize the interoperability of these components and the positive influences leading to the success of SBM. Following the suggestions of Guetterman and Fetters (2018), we also discuss case examples from CDP data, demonstrating the positive outcomes businesses have achieved through the integration of these ESFs in their organizational strategy and business models.

We will discuss the results of this study along with some best-case examples from CDP data through the lens of sustainable "value" creation, delivery, and capture. Details on most of the identified industrial practices and relevant ESFs are also explained in the context of the business model components.

## 4.1. Sustainable value creation

Sustainable value creation refers to the key activities, key resources, and key partnerships that generate economic, ecological, and social value for the stakeholders (Evans et al., 2017). The conventional focus of value creation for customers has greatly shifted in recent years toward a larger system of stakeholders and diverse value concepts related to environmental, social, economic, and psychological perspectives of value building (Laukkanen et al., 2021). Figure 2 shows the graph for ESFs related to each component of value creation and frequency of relevant codes as found during CDP analysis.

### 4.1.1. Key partnerships

Key partnerships play a cornerstone role in any sustainable business model. There could be several reasons for any firm to forge a partnership. For instance, optimization of business models, integrating climate risks into business strategy, implementing green supply chains, and acquiring renewable resources are potential key benefits of a partnership.

Companies seeking to introduce eco-friendly strategies must engage stakeholders along their value chains. CDP surveys provided us with some ground facts on **collaboration strategies** for building a sustainable business model. In their CDP reports, top-performing companies have demonstrated verifiable plans for surveying their suppliers and acquiring information on the treatment of raw materials. Regular on-site visits to monitor the production of key raw materials help in mapping structural sustainability in the supply chain. Companies also send **regular questionnaires** to measure key performance indicators and suppliers' impact on climate change. A surveying tool by The Sustainability Consortium known as "The Sustainability Insight System (THESIS)" is getting popular as it helps in determining the strategic direction of suppliers in meeting net-zero emission targets (Asif et al., 2022). Firms can learn from Walmart's efforts in developing collaborative environmental practices with their suppliers. Walmart's implementation of THESIS, Project Gigaton, and Blockchain Technology has allowed their suppliers (mainly farmers) to reduce 213.6 million metric tons of emissions from their operations in 2019 alone (Global, 2020).

Demonstration of waste handling technologies in industrial conferences and technology parks allows for **industrial agglomeration** leading to economic and centralized waste management (Cui et al., 2022). However, SBMs not only succeed

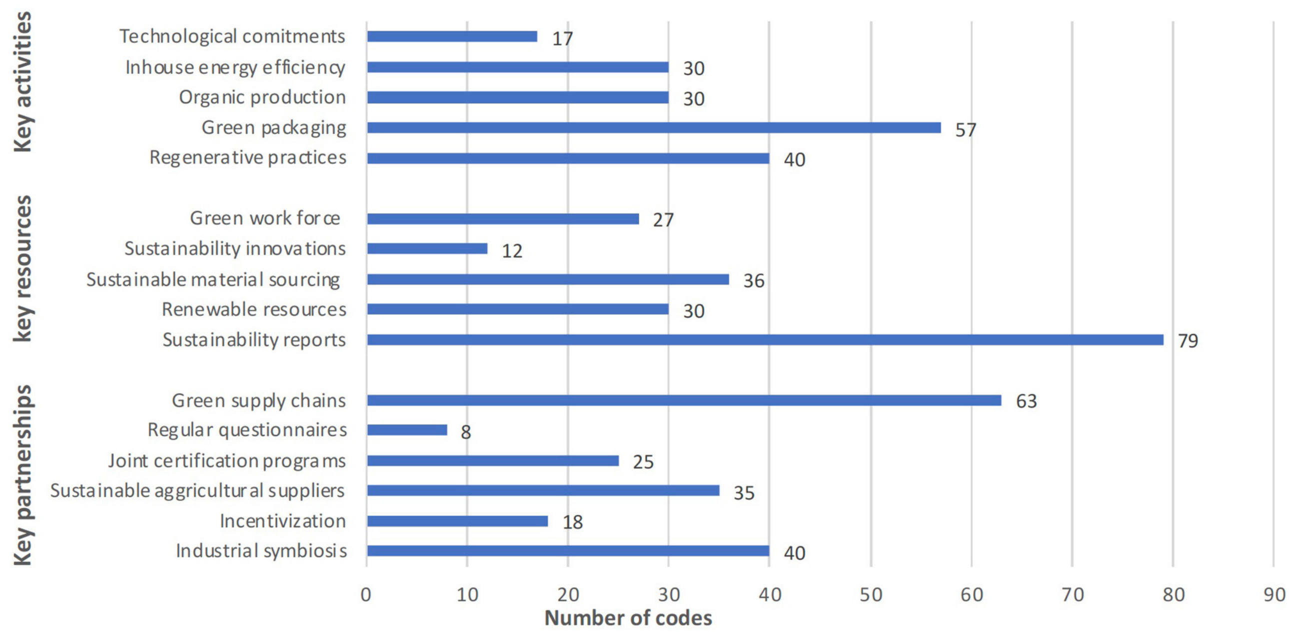


FIGURE 2
Value creation components, relevant ESFs, and codes count.

through technology implementation or business innovations but innovations in the SBM itself are also major drivers (Yang et al., 2017). In this regard, SBM innovation demands reconceptualization concerning its relations with stakeholders. Many companies are transforming their relationships, enabling them to move from a transactional mindset to trust-oriented and sustained relationships with primary and secondary stakeholders (Evans et al., 2017; Serna et al., 2022). Secondary stakeholders including universities, communities, NGOs, media, and governments are the entities that do not directly engage in business transactions with a company but their collaboration is still crucial for SBM success (Bolton and Landells, 2015). The ecological system also acts as a primary stakeholder as it impacts the economic situation of a firm and "affects or gets affected" by the business. Therefore, SBM value should flow among all stakeholders, considering the natural environment and society as primary stakeholders, to enhance more opportunities for SBM innovations (Den Ouden, 2012).

Adopting **GSCM** enables firms to take a systematic approach toward reducing scope 3 emissions by engaging with key players in the value chain. Following the GSCM practices of eco-designing and **green logistics**, companies provide an accumulated set of instructions to their suppliers on reducing emissions (Eltayeb et al., 2011; Asif et al., 2020). Normalizing the practice of **industrial symbiosis** will potentially help to achieve net-zero carbon emission targets by the mid-century. Industrial symbiosis also enables a **circular economy** by allowing firms to transfer their waste or by-products to another firm as their production inputs (Yazan et al., 2020). Firms also collaborate with concerned communities and NGOs to widen the outcomes of sustainable supply chain practices (Sharma et al., 2021).

### 4.1.2. Key resources

Orientation and management of important human, physical, intellectual, emotional, and financial resources are key to sustainable business model development. Let's consider some of these resource types, through which companies can successfully lower their scope 1, 2, and 3 emissions and enhance sustainability performance.

Raw materials are considered the primary resources for food, beverage, and tobacco manufacturing companies and are mostly sourced from **crop-yielding** facilities. Acute and **chronic physical climatic conditions** such as cyclones, floods, earthquakes, wildfires, rising sea levels, and rising global mean temperature should be continuously monitored as they greatly affect the production of agricultural raw materials (Global, 2020). Innovative technologies that deliver sustainability are considered paramount resources allowing for sustainable value creation and delivery for the customers and other stakeholders (Cui et al., 2022). Sustainability-oriented innovations (SOIs) have also become a major driver for environmental and social developments (Nakandala et al., 2023). However, the success of SOI firms depends on their strong exploration and exploitation capabilities, including raw material sourcing, and management of internal and external resources with a clear orientation (Behnam and Cagliano, 2019).

Energy is another major resource central to all operations of food, beverage, and tobacco firms. The usage of non-biodegradable fuels is a major cause of GHG emissions. Enterprises now strive to shift from non-renewable energy sources to meet their electricity and utility needs sustainably. The case example of a renowned Japanese company, Ajinomoto, is commendable as they shifted their fuel usage from petroleum oil to renewable power resources and demonstrated their positive impact on global warming through

CDP reporting (Global, 2020). Such approaches to acquiring **renewable and reusable physical resources** are critical for food businesses to become carbon neutral by mid-century.

Farmers serve as the most vital human resource for food companies, as they play the pivotal role of supplying agricultural raw materials. A firm can reduce carbon emissions by yielding **organic production** through collaboration with farmers. **Farmer awareness programs** can educate them on the importance of organic production and mitigating GHG emissions. Companies can achieve a cleaner and greener environment by allocating their key resources to emission-intensive processes, promoting organic yielding of crops (Jolink and Niesten, 2015).

Not only sustainable raw material suppliers but the presence of a team of experienced and knowledgeable supply chain managers nurture the path to achieving net-zero targets (Blanco et al., 2016). Lack of motivation, management will, training, and **sustainability awareness** among employees are some impediments to low-carbon transitions (Sharma et al., 2021). **Effective communication**, **training**, incentives, and workshops on environmental issues can eliminate some of these barriers and promote sustainability knowledge within the firm. Environmental documentation including environmental policy, pollution prevention plans, emergency responses, environmental compliance reports, and environmental certifications also need to be communicated among employees. Following these human resource practices cannot only lead to the successful implementation of SBM but can also promote the state of GSCM and circular economy for the company (Pinto, 2020).

**Financial resources** predominantly affect the firm's efforts toward a low-carbon transition. Surveys, such as CDP, have proven that private sector firms can effectively achieve carbon reductions by leveraging operational economies, provided they possess a keen awareness and skillset in this domain (Blanco et al., 2016). With growing carbon pricing and induced carbon taxes, firms are compelled to play their role in achieving a low carbon economy while also benefiting their sales. **Intellectual** and **emotional resources** also play a credible role in sustainability promotion. Grasping the emotions of customers through **motivational campaigns** and rebuilding marketing policies according to their expectations will certainly lead toward reaching net-zero targets. Moreover, the urge for healthy, delicious, and organic food is fueling new trends of this era, allowing firms to promote **biodiversity** and **natural food processing** to appeal to new consumers (Jolink and Niesten, 2015). For instance, Danone Foods from France acquired White Wave in April 2017 and drastically shifted toward the production of plant-based organic foods and drinks. This strategy brought a wider choice to "flexitarians" (seldom vegetarian, often meat eaters) and promoted biodiversity as well (Global, 2020). Similarly, companies can use agronomic research to utilize present and new resources for building sustainable and **resilient supply chains**.

### 4.1.3. Key activities

As our focus is the food, beverage, and tobacco sector, where the primary product consists of agricultural ingredients and raw materials that originate from crops and farming. So far, companies have made several strategic moves to implement **sustainable cultivational practices**, enabling carbon emission-free production. Biodiversity considerations, substitutional additives, weed management, soil health management, fertilizer and livestock feed management, crop rotation, and biological pest control are proof-based key practices helping CDP reporting agricultural firms to reduce their emissions and long-term costs simultaneously. Companies can also eliminate the GHG emissions in the livestock industry by using feed rich in amino acids as they are fully digestive to livestock and 100% absorbed by their bodies. Hence, zero concentration of carbon dioxide and nitrogenous compounds in their wastes leads to lower global warming (Global, 2020). General Mills associated with South Dakota University announced the opening of a state-of-the-art oats laboratory to conduct research in sustainable farming and support oat growers to develop resilient and profitable supply chains (Global, 2020; Caffe-Treml and Breeder, 2021).

Transformation of key activities is also critical to address the **changing consumer trends**. Barry Callebaut, a chocolate manufacturing company, estimated that customers are willing to pay 5-15% more for sustainable chocolates. The company embraced this new shifting trend and accordingly generated another stream of profit for the company. They committed to the "Forever chocolate program" to manufacture carbon-neutral chocolate products, taking revenue advantage while benefiting the environment (Global, 2020). Sustainable businesses also tend to integrate **pollution control, pollution prevention, and product stewardship** into key activities of their business to gain competitive advantage and dynamic capabilities (Klassen and Whybark, 1999). Pollution control refers to keeping pollution and emissions under specified limits as per industrial regulations or **environmental certification** requirements. This requires a transformation of key activities in their waste treatment plants and **emission-capturing technologies**. Pollution prevention refers to reducing or eliminating pollution by improving manufacturing and processing activities e.g., through efficient use of raw materials, energy, and water. Product stewardship calls for the integration of environmental sustainability across the design, production, and distribution activities and owning the responsibility of reducing emissions across the lifecycle of a product (Albertini, 2013).

Furthermore, **sustainable material sourcing** in line with **eco-friendly product design** is a crucial element of SBM, allowing the manufacturing and processing of **carbon-positive products**. Raw material processing plants driven by **renewable** and **biodegradable** fuels ensure **green manufacturing** (Asif et al., 2020). Eliminating manufacturing and packaging waste as part of key activities also enhances the positive outcomes of SBM. While adopting **regenerative practices**, companies should also strive to use non-plastic packaging i.e., paper bags and compostable packaging. In 2019, Coca-Cola company initiated a plan to replace hard-to-recycle material shrink wraps with 100% recyclable cardboard packaging, removing 4000 tons of single-use plastic per year across their territories (Bates, 2019). Besides this, they tend to change the color of Sprite bottles from green to transparent to avoid color waste and make them reusable (Global, 2020).

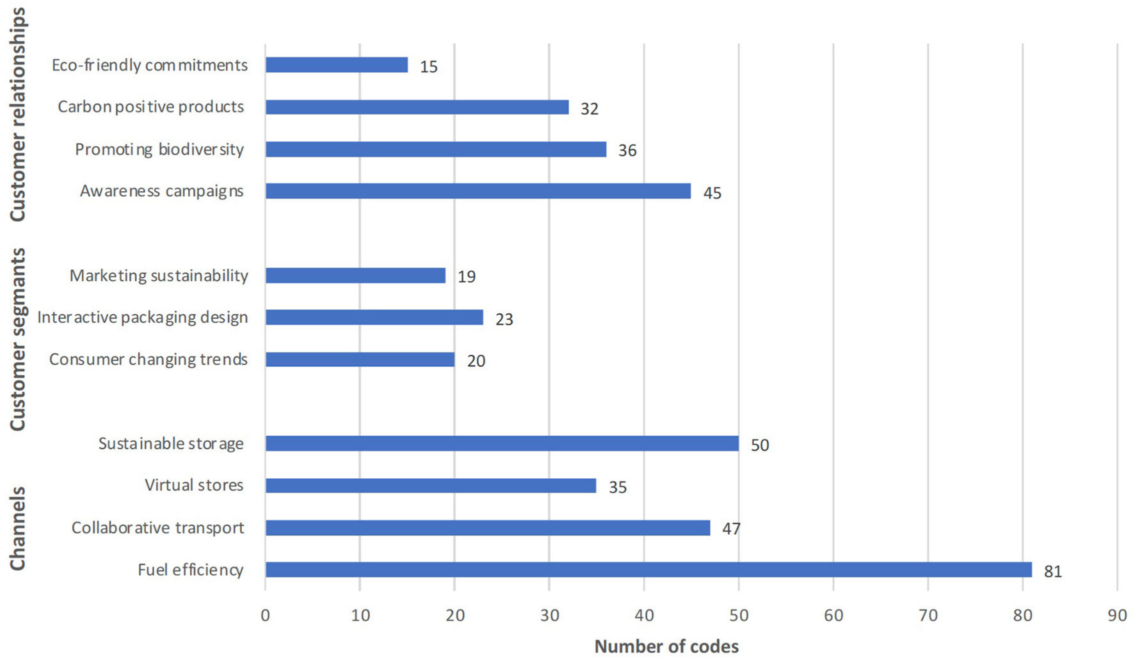


FIGURE 3
Value delivery components, relevant ESFs, and codes count.

## 4.2. Sustainable value delivery

Value delivery refers to the physical distribution and accompanying communication that allows firms to deliver tangible and intangible components of value proposition to their customers (Norris et al., 2021). Figure 3 demonstrates critical ESFs relevant to channels, customer relationships, and customer segments that enable sustainable value delivery in a strategic business environment.

### 4.2.1. Customer relationships

In terms of customer engagement on environmental issues, motivating customers to buy certified sustainable products is one of the key challenges concerning the premium prices (Ali et al., 2019). This is also evident from companies' CDP data but following a **green marketing strategy**, some firms have introduced **incentives to shift customer interests** toward environmentally friendly products. These firms also manufacture returnable products and maintain **on-site recycling plants** to develop a reciprocal relationship with their customers while reducing the environmental impact of their core activities (Global, 2020). The case of Del Monte Foods is worthwhile as they motivated customers to participate in the initiative of the "Sustainable Packaging Coalition" by labeling "how to recycle" on their packaging. This helped consumers to learn how to recycle accurately and where to find information specific to their municipality (Foods, 2021). Therefore, one of the key opportunities in the environmental context is to educate consumers on returnable and recyclable packaging through effective labeling and marketing schemes (De Boer, 2003). Another innovative technique is to customize labels and stickers of products with characters and multi-games for all ages to portray recycling.

Including sustainability stories of clients in annual reports and inviting them to the company's sustainability seminars not only strengthen customer relationships but also builds their confidence in the positive outcomes of customer-led sustainability programs (Eltayeb et al., 2011). Recording the climate change risk management process and achievements toward net-zero targets in annual sustainability reports and distributing it among the customers also draw positive outcomes in terms of **customer collaborations** and business growth. For instance, Arca continental SAB De organization publishes an integrated annual report which addresses sustainability making this document accessible to everyone. They disclose major information about environmentally friendly products such as Sprite blue bottles which is a 100% circular product and re-manufacturable to an infinite number of times (Global, 2020). **Published reports** will provoke customers to support the companies in their **selling growth** and to persistently strive toward achieving global net-zero targets.

Customer relationships not only stand on the environmental performance of a firm but also the perceived quality, lead time, and customer service. Just like specialty foods, sustainably manufactured foods also require distinctive approaches in retailing and after-sale customer experience (Calvo-Porral and Levy-Mangin, 2016). This fortifies the need of integrating **customer expectations** into key activities, channels, and cost structures of SBM. Consideration of customer engagements in SBM cannot only expand the customer segment of a firm but can also enhance cooperation in reducing the carbon footprint related to the flow of products in the supply chain (Williams et al., 2008).

### 4.2.2. Channels

Companies can achieve the target of low carbon emissions by integrating some pragmatic approaches in the channeling of products from upstream to downstream. Virtual stores and retail markets are two major channels for any company to deliver valuable products and services to their customers. **Virtual stores** or **online retailing** tend to centralize the resources, customers, and key partners while gaining benefits of the universal nature of the world wide web, geolocation tools, availability of personal technology and high-speed data networks (Amblee and Bui, 2011). All the partners share the same values, resources, and customers on e-commerce websites, reducing the intensity of resource consumption and promoting sustainability. However, a company sharing its resources on online platforms may face Enterprise Resource Planning (ERP) related barriers such as interoperability issues, scalability and performance challenges, and customization challenges (Asif, 2018). Therefore, it is critical for businesses to monitor and address compatibility issues as they make any changes in their channeling operations.

Companies implement various logistics plans to address potential environmental risks**. Collaborative transport** is one of them, allowing businesses to reduce empty mileage across borders and switch to low-emission transportation modes i.e., electric and hybrid vehicles. Among several organizations that reduced their scope 3 emissions by optimizing transportation and fuel consumption, Clean Cargo Working Group is noteworthy. It is preferred by many companies as third-party logistics providers to transfer their goods with less fuel burning and lower carbon emissions. Another example is the MARS group which offers carbon-neutral parcel deliveries for retailers via delivery partner DPD. Parcel packaging provided by the DPD is also fully recyclable. Lightweight material and low water content of packaging minimized scope 3 emissions and had a wide effect on diminishing carbon footprints (Global, 2020).

Collaborative transport is not enough to reduce scope 3 emissions, but other measures should also be taken. In retail markets, companies should replace high energy-consuming coolers (refrigerators) with energy-efficient and HFC-free coolers. This can be done by replacing R12a and R134a with **$CO_2$-based refrigerant gases** (Asif et al., 2022). A famous beverage brand Coca-Cola took a step ahead as they elevated the use of energy-efficient super coolers at consumer outlets (Global, 2020).

Recognizing that environmental degradation is a major risk posed to nature, companies should actively educate their supply chain partners on low-carbon casting packaging and transportation, thereby ensuring **resilience** in supply chains. The package's ability to support the efficient transport solutions (Williams et al., 2008) and management of costs and incentives related to the **packaging waste logistics** (Pazienza and De Lucia, 2020) add to the effectiveness of SBM. Furthermore, increasing the ratio of bio-based ingredients and Polyethylene terephthalates (PETs) in packaging can lead to net zero emission targets as **recycled PETs** have a depleted ratio of carbon as compared to other plastics (Benavides et al., 2018). In their prospect of becoming a net zero company, Coca-Cola also used recycled plant-based plastic and PETs and reached a 12% reduction in carbon footprint in 2019. Their transition aim is to use bio-based PET in all their packaging by the end of 2025 as **renewable packaging** has far less impact on climate change (Global, 2020).

### 4.2.3. Customer segments

The customer segment component of SBM refers to the individuals (B2C) or companies (B2B) that a business intends to target and serve. In the case of sustainable business models, the customer segment comprises individuals/companies who value the environmental performance of a product/service. Companies also tend to target specific sectors of customers from whom they can capture value in terms of revenue. In the food, beverage, and tobacco sector, customer segments can be highly diverse based on the type of products and age groups of consumers ranging from baby boomers to Generation Z consumers. However, food business proposing carbon neutrality and net-zero values to their customers should meet their expectations by generating substantial product/service value through their partnerships, resources, channels, and key activities while capturing sustainable value for their own business through cost structures and revenue streams.

The segment of **sustainability-conscious customers** is boosting and as per the outcomes of the 2020 Mckinsey US consumer sentiment survey of more than 100,000 US households, 60% of respondents agreed to pay more for sustainably packaged products (Frey et al., 2023). A NielsenIQ report also revealed that more than 66% of consumers tend to spend more on products from a sustainable brand and that consumer expectations around sustainable branding had a positive correlation with the increase in millennials and Gen Z consumers (North, 2022). Moreover, a 2022 report by First Insights claimed that around 90% of Gen X consumers are willing to spend an additional 10% or more for sustainable products compared to around 34% two years ago (Petro, 2022). Therefore, sustainability goals not only drive innovation and build resilience, but also open new markets, channels, and customer segments.

However, the current sustainability trend also demands further research to incorporate sustainability aspects for low-income customers. There is an opportunity to expand the consumer base by making claims in marketing endeavors and **product labeling**. Most successful claims as reported by Frey et al. (2023) include **animal welfare** (cage-free, free range, sustainable grazing), environmental sustainability (compostable, eco-friendly), organic positioning, **plant-based** (vegan), social responsibility (fair wage, ethical), and sustainable packaging (plastic free, biodegradable) and products with these **ESG** (Environmental, Social, and Governance) claims averaged 28% growth over the past five year period. Moreover, to sustainably capture the food market and extend their customer base, businesses need to continuously monitor and improve their sustainability aspects including information technology, circular economy, dynamic capabilities, value chain, and stakeholder engagement (Goni et al., 2021). Unilever was able to capture new customers in water-scarce markets by promoting "sunlight dishwashing" liquid that used much less water than other counterparts and achieved category growth of more than 20% in those markets (Sustainability, 2020).


FIGURE 4
Value capture components, relevant ESFs, and codes count.

## 4.3. Sustainable value capture

Value capture includes the processes for securing profits from value generation and delivery and distributing the profits among relevant stakeholders such as suppliers, customers, and other partners (Chesbrough et al., 2018). It also includes integrated processes for controlling the costs of realizing and creating value. Figure 4 shows important ESFs to capture substantial value for the business and relevant stakeholders.

### 4.3.1. Cost structure

The cost structure essentially represents the aggregated expenses required to operate the business model. Every company which owns a sustainable model would make significant investments in low-carbon manufacturing and operations. Although pursuing carbon-positive production and manufacturing entails higher costs, it enables diversified long-term benefits not just in terms of emission reductions but also increased productivity and profitability (Trumpp and Guenther, 2017).

In general, sustainability initiatives accumulate high costs for the business but avoiding these initiatives can not only threaten the survival of the business but dramatically increase the costs in the form of fines and carbon taxes (Albertini, 2013). Corresponding to the amount of carbon dioxide emissions, a **carbon tax** can impose a high risk to the survival of a company. For instance, increasing **fuel taxes** on transport to facilitate decarbonization is another risk as it increases the logistics costs for the business (Sterner, 2007). Moreover, the usage of non-renewable resources in processing and manufacturing leads to considerable carbon emissions, resulting in the loss of business and customers. On the other hand, investment in energy-efficient technologies and renewable energies can increase companies' **capital investment**. Companies that rely on innovative technologies to meet their sustainability needs often face low Returns on Investments (ROI) (Isik, 2004)**.** Furthermore, in organic production, the manufacturing of amino acids, processed seasoning, and sustainable fertilizers increases the direct costs for the business but improves their agricultural sustainability (Global, 2020). Shifting from petroleum oil to **renewable fuel** usage will lessen the scope 2 emissions but at a tradeoff of increased costs. Similarly, **carbon disclosures** and environmental certifications require human and financial resources but provide the company with new marketing avenues and credibility (Hahn et al., 2015). However, the costs of non-compliance and avoiding sustainability initiatives are far more than the costs of undertaking these initiatives. Therefore, businesses need to rejuvenate their investment strategies and cost management with a broader strategic vision. Pessimists may argue about the high costs of sustainability, but the benefits certainly outweigh the costs in terms of new revenue streams, customer retention, market shares, and reputation (Eltayeb et al., 2011).

Businesses new to sustainability initiatives can begin with win-win strategies i.e., initiatives that cut costs and improve environmental performance simultaneously. For instance, the study of Nakandala and Lau (2018) emphasizes local sourcing of fresh food and vegetables as it reduces logistics costs and emissions. Similarly, companies can improve their economic and environmental sustainability position simultaneously through cost-saving initiatives such as **cogeneration of energy**, **waste sharing, transportation sharing, and water re-usage** (García-Muiña et al., 2020). Companies can also stimulate long-term sustainability programs and reduce their carbon tax by adopting innovative and efficient technologies, reducing on-site energy consumption, using **regenerative plants**, and manufacturing carbon-neutral products. For instance, Altria's group of companies invested in the latest technology to convert their coal-fired boilers to natural gas-based boilers in three of their major manufacturing units. They completed the project in 2014 with a total cost of $2,950,000 and were able to generate annual savings of ∼$3,200,000 as reported in 2020 (Global, 2020). The case of 3M is also commendable as the company saved $2.2 billion since the launch of its "pollution prevention pays" (3Ps) program involving eco-designing, green manufacturing, and reusing waste from the production (Sustainability, 2020).

### 4.3.2. Revenue stream

Manufacturing and marketing low-carbon emission products are anticipated to augment market demand, thus increasing revenue for a company. To survive in the perpetually evolving market landscape, businesses should build up **dynamic capabilities** and **change management** skills to cope with the shifting trends. Adaptability and the ability to sense and seize opportunities are likely to enhance the revenue streams of a company.

Although historical research has argued on the negative impact of reactive environmental initiatives on the financial performance of a firm (Cordeiro and Sarkis, 1997; Klassen and Whybark, 1999; Lankoski, 2008; McPeak et al., 2010), in-depth studies comprising metadata have demonstrated positive financial outcomes for proactive environmental actions i.e., market-based returns (price-earnings ratio, price per share) and accounting based returns (return on equity, return on assets, return on investment) (Clarkson et al., 2011; Albertini, 2013; Beckmann et al., 2014). This has reinforced the famous Porter's depiction of pollution as an **economic waste** of a firm and achieving a "win-win" situation through corporate environmental management (Porter and Van Der Linde, 1995). Therefore, companies should look at the brighter side, considering environmental management an opportunity to enhance the financial returns for their company.

There is an economic term called **tradeoffs**, i.e., compromising on one thing to achieve another. To attain a sustainable business strategy firms should make some hard decisions on compromising the revenue for at least a short-term (Beckmann et al., 2014). For instance, using **recyclable materials** may cost more to firms but reduces their scope 3 emissions. To mitigate the tradeoff, companies can pursue smart packaging techniques to outweigh the cost disadvantage and reach a win-win situation (Williams et al., 2008). A Belgium company named Anheuser Bush identified a packaging preference by transitioning from one-way to **returnable packaging.** They first implemented the initiative in collaboration with waste collectors in Colombia to facilitate the retrieval and refilling of one-way bottles. Using this approach, they reduced the carbon footprint by more than 50% and saved $50 million in energy costs with negligible alterations to revenue streams (Global, 2020). Therefore, sustainability initiatives provide diversification in revenue streams for a business. Businesses not only generate revenue through B2B or B2C sales, but also through government-paid carbon credits, green tax incentives, income generated through **waste sharing** and **transport sharing**, and selling self-generated **renewable electricity** to the grid etc.

As discussed earlier, changing trends in consumer behavior present opportunities for companies to increase their revenues—**adaptability** is the key. Adaptability should be an integrated factor of "business strategy" allowing companies to take strategic actions and achieve competitive advantage in response to the changes in the external environment (Cui et al., 2022). Cases of high revenue-generating firms reveal that their environmental business strategies—clean technology, sustainability vision, product stewardship, and pollution prevention—not only add economic value to SBM but also social value in terms of poverty alleviation and fair distribution (Evans et al., 2017). The historical case of Watties marked a significant breakthrough as they initiated the "Grow Organic with Watties" campaign in partnership with their produce suppliers who couldn't meet the ever-increasing demand for organic vegetables. In terms of economic value, the initiative resulted in higher contract prices for farmers, charging as high as 310% of conventionally produced vegetables. Watties also capitalized on the **shift in consumer trends**, charging a premium of over 100% to their buyers in Japan while developing their market position as an environmentally progressive food producer (Global, 2020).

## 4.4. Industrial implications

Various authors have suggested different methods including experimentation, the use of trial-and-error techniques, simulations, and pilot programs to discover sustainable business models for a range of industrial sectors despite the high resource needs and associated risks (Evans et al., 2017). However, we followed the method of analyzing real companies and proposed a generic business model that any company from the food, beverage, and tobacco sector can adopt to target the customer segment that appreciates net-zero enabled products or services. Being business-oriented research, this paper provides manifold implications for the food, beverage, and tobacco industry. Major contribution includes the development of the environmental tier of a sustainable business model (Figure 5) with integrated ESFs that can potentially help the firms to identify, implement, and monitor best green practices, business strategies, environmental initiatives, and compliances that lead to the achievement of net-zero emission targets.

Companies proposing net-zero value to their customers are often subsidized by value chain partners, NGOs, and governments. This enhances the intrinsic motivation for developing a circular economy where the product's end-of-life is managed through collaborative life cycle assessments and adoption of the 3R (reducing, reusing, and recycling) principle. Based on the importance of collaborations highlighted in literature and CDP disclosures, we also incorporated "collaboration motivations" and "collaboration benefits" as additional components of win-win SBM.

The presented environmental tier of SBM can act as a generic model for any food, beverage, or tobacco firm to systematically manage and control their operations toward meeting net-zero emission targets. Interested companies can select the ESFs in relevance to their business and for each of the selected ESF, they can identify relevant practices and initiatives from Table 3. Moreover, the study findings are critical for companies in the initial stages of setting environmental goals and want to determine low-cost environmental initiatives, to begin with. Following the recommendations provided in the "Discussion' section under cost structure and revenue stream, companies can learn to manage the trade-offs and adopt win-win strategies to initiate sustainable business modeling.

The findings of the study also provide valuable insights into the strategies and practices that businesses can incorporate into their processes to achieve sustainability goals. With a

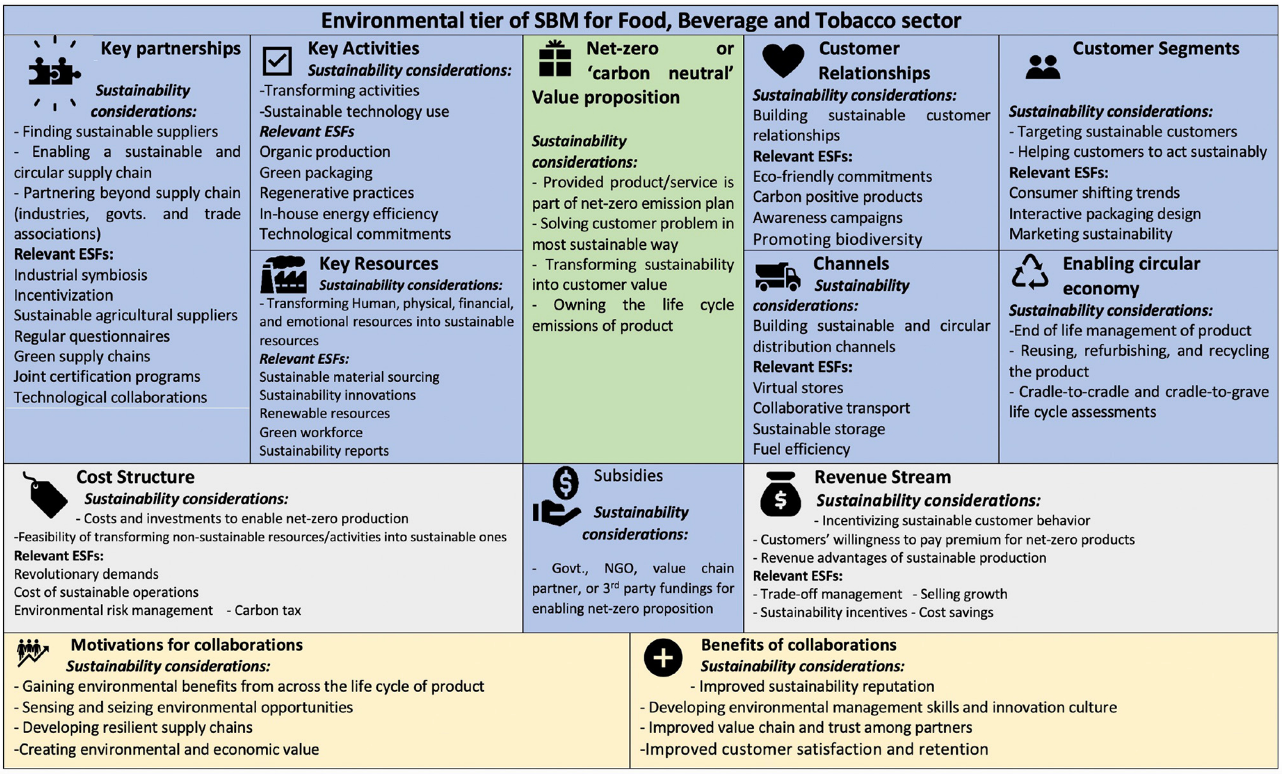


FIGURE 5
Environmental tier of sustainable business model canvas.

better understanding and implementation of ESFs, businesses can improve their business process management maturity by aligning their operational strategies with sustainability objectives. Therefore, this research can be used as a guide to integrate environmental consciousness into business models and improve their overall maturity in managing sustainable processes. Finally, in response to the rapid shift in food production and consumption trends, it has become indispensable for firms to develop sustainable business models that create, deliver, and capture value not only for the customers and business but also for the environment and society.

## 4.5. Theoretical implications

Our study reinforces the argument of Boons and Lüdeke-Freund (2013) that a major challenge to the success of SBM is the engagement efforts of a firm in their interactions with internal/external stakeholders and the business environment. Analysis of real company data depicts the veracity of "instrumental stakeholder theory" as it explains how a firm's actions toward building stakeholder relationships impact the performance of the firm. Our analysis and recommendations around "key partnerships," "key resources," and "customer relationship" suggest a strong connection between the success of environmental initiatives and stakeholder engagement. Moreover, by proactively integrating stakeholder expectations in environmental strategies and initiatives, firms can gain a competitive advantage in novel sustainability markets, and ultimately enhance their profitability too. "Theory of collaborative advantage" is another practice-based theory about the management of inter-organizational partnerships to achieve mutual benefits. The theory postulates two major reasons for collaborations i.e., self-interest or moral reasons. Self-interest motivates the firms to collaborate and gain certain financial and non-financial advantages for their firm while "moral" reasons motivate the firms to collaborate for the betterment of the community and environment (Huxham, 1996). Furthermore, the founders of the theory call for further development and testing in the moral reasoning domain (Vangen and Huxham, 2013), and therefore, our research contributes significantly as it hypothesizes that the primary reason for businesses to undergo collaborations concerns the environment and community, while secondary reasons include market or financial advantages.

Our research highly aligns with "systems theory" as we found a high degree of overlapping, cross-sectioning, and interdependence of ESFs across all constructs of the business model. SBMs are complex structures consisting of almost everything a firm does to offer a product/service to its customer including sourcing, production, packaging, retailing, and handling returns. For instance, a firm's decision to change the packaging material in their physical resources will certainly impact their packaging process (key activities), which in turn affects the cost structure and channels (how these new packages are handled), leading to a change in partnership and revenue stream. Therefore, a systems approach will allow firms to become strategic in their decision-making and timely check the impact of new practices and initiatives across the business model and supply chain. This is obvious to most of the companies' higher managements and they have started moving from incremental improvements to systematic approaches that create a net positive impact (Winston, 2022).

## 5. Limitations and future directions

Provided the scope of the study, this paper has addressed scholarly concerns of ready-to-implement SBM for food, beverage, and tobacco firms considering the high consumption of this sector and escalating consumer demands for products with net-zero emissions. However, various limitations were identified during the course of the research that are mentioned below along with the future avenues for their resolution.

**Exclusivity of analyzed firms.** One of the highly argued limitations of CDP-based research is the exceptionality of firms voluntarily disclosing their environmental information to CDP. Since the beginning of CDP in 2000, it has persuaded the world's largest listed firms to disclose their carbon data on ethical grounds (Depoers et al., 2016), and therefore, its portfolio is dominated by leading corporates in terms of market share and CSR. Researchers should analyze the carbon disclosure of firms included in the CDP database along with other SME-oriented databases such as OECD, GRI, and IFAC to develop sustainability models with a wider outreach.

Furthermore, considering the credibility issues around the voluntary and self-reporting nature of CDP data, our paper incorporated scholarly articles in the discussion section that used primary industrial data to identify the most critical environmental sustainability factors.

**Nature of data.** Our study has approached the research questions through a cross-sectional analysis of firms that reported to CDP in 2020. Therefore, our study is unable to show trends and changes in carbon reporting over a longer period. Future researchers can adopt a time-series model to determine the positive impacts of firms' environmental initiatives over a time range of a few years. In such research, the data complexity can be managed by applying product range-based filters to develop generic net-zero SBMs for different product categories. Moreover, our research outcomes are only applicable to the food, beverage, and tobacco sector, but provides an opportunity and framework template for future scientists to develop SBMs specific to other industrial sectors.

**Research is dominated by the environmental aspect of sustainability.** Our paper is not highly focused on the economic and social tiers of SBMs as the motivation was to develop a comprehensive model for reaching net-zero emission targets. Further research is required to develop integrable tiers of social and economic SBMs that also fortify the firm's efforts around net-zero plans. Researchers can also demonstrate valuable insights by analyzing the impact of such net-zero based SBMs on social, economic, and policy dimensions of corporate business.

## 6. Conclusion

In conclusion, our paper presents a novel approach toward developing a sustainable business model in the food, beverage, and tobacco sector. The model is driven through a comprehensive analysis of 252 food, beverage, and tobacco firms that disclosed their environmental data to CDP in 2020. By analyzing their qualitative responses using NVivo software, we identified a range of environmental sustainability factors (ESFs) helping the firms to meet their emission reduction targets. The ESFs were prioritized and mapped with various components of the business model canvas, to effectively propose a "net-zero" or "carbon-neutral" value proposition to customers. Considering the theoretical and practical implications, our research has addressed a significant gap in terms of real data-driven SBM exclusive to food, beverage, and tobacco firms and provided a practical guide for firms to initiate strategic business modeling and achieve their net-zero emission targets. The research also implied the importance of supply chain collaborations and effective engagements with stakeholders as a critical success factor of SBM. Moreover, it provides a set of 150 green practices aligned under relevant ESFs so that start-up firms and SMEs can select best-fit green practices and operationalize their SBMs. Finally, the research opens a doorway for the development of more sector specific SBMs that can lead businesses to not only add value to their business and customers but also to society and the environment.

## Author's note

The author team of this paper have been conducting research on environmental management of food sector for past 4 years and this paper is 3rd in series of their high-quality journal articles. The first one related to green supply chain management adoption in food sector (published in Journal of Cleaner Production) and the second one was about Life Cycle Assessment (LCA) based case analysis of high selling, ready to eat, food products (Corporate Social Responsibility and Environmental Management Journal). While developing this third paper, we were captivated by high quality literature from Frontiers in Sustainable Food Systems (FSFS) in this field. After analyzing the findings of this paper against the aims and scope of FSFS, we found a high degree of relevance and decided to publish it in this esteemed journal. Scope of the paper extends from strategic organization management to environmental sustainability management and therefore, practical contribution of authors from diverse disciplines was important for successful completion of this paper.

## Data availability statement

Carbon Disclosure Project (CDP) database access is subscription based. Western Sydney University (WSU) provided access to the dataset analyzed in this research. Requests to access the data should be directed to www.cdp.net.

## Author contributions

MA: conceptualization, methodology, investigation, visualizations, formal analysis, and writing-original draft. HL: supervision, project administration, and formal analysis. DN: validation of the results, data curation, and editing. HH: writing-review and editing. 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



## Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2023.1214490/full#supplementary-material

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# Putting food in the driver's seat: aligning food-systems policy to advance sustainability, health, and security

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Food is a basic need, but seldom a basic policy area. Food systems are widely governed by disconnected policies distributed across a range of sectors including agriculture, education, health, environment, economy, and security. Failure to align food system strategies often results in these disparate policies operating at cross-purposes. Conventional food production and consumption practices contribute to biodiversity decline and climate change, cause diet-related health problems, are associated with worker exploitation, and create national security risks. Drawing on agroecology for cohesive national food strategies can provide benefits across all these sectors: supporting public health, environmental sustainability, economic stability, social cohesion, and national security and sovereignty.

KEYWORDS

**food policy and governance, net zero, sustainability, health, food security, food systems**

## Introduction

The importance of food can hardly be overstated. Food is not only a basic need but also a key economic pillar with direct impacts on many drivers of economic and social function. Food systems, which comprise all the actors and relationships involved in growing, producing, manufacturing, supplying, and consuming food, involve not only agriculture and fisheries but also food manufacturing, retail, service, consumption, and waste management. In addition to providing the populace with nutrition and sustenance, these systems support many levels of commerce, interact with and alter ecosystems, profoundly influence public health, and often affect foreign policy. Food is also a vital cultural component and, at its best, a powerful convener supporting community cohesion.

Despite this centrality, food has taken a back seat in policy development. Rather than approaching the food system as a policy area, food systems are generally governed by disparate policies scattered across numerous areas such as agriculture, health, environment, education, welfare, and economic policy. Lacking integration, these policies often operate at cross-purposes, with food-related goals in one area undermining progress in others.

At the most macro scale, the global move toward easily consumable food with year-round availability has functioned in opposition to sustainability objectives. Specialization, intensification, and consolidation of food production have massive environmental costs: the food system globally is responsible for approximately 30% of greenhouse gas emissions (Crippa et al., 2021) and is the single largest factor in biodiversity decline (Benton et al., 2021). The predominance of highly processed food is also a major factor in the global rise of diet-related diseases, such as obesity, type 2 diabetes, heart disease, and certain cancers (Rico-Campà et al., 2019; Srour et al., 2019). Additionally, large-scale consolidation creates an imbalance of power between industrial decision makers and the consumers and suppliers on whom the system relies (Oxfam, 2022).

These issues are now coming to a head in Wales, with the impacts of Brexit including increasingly divergent policy across the United Kingdom countries, deregulation at the United Kingdom level, and opportunities to develop a unique statutory framework for the Welsh food system. Wales already has the Well-Being of Future Generations (Wales) Act 2015, which mandates that Welsh public bodies work together to preserve quality of life for succeeding generations and includes seven interconnected well-being goals addressing health, equality, prosperity, resilience, community cohesion, cultural continuity, and global responsibility. In the context of food system policy, this act provides for better decision-making by ensuring that public bodies take an integrated and collaborative approach to long-term impacts. However, coordination challenges remain pronounced in Wales due to the continued fragmentation of food policy. For example, the Welsh government's recent efforts to implement a free school lunch program as a means of improving children's nutrition, reducing health inequalities, and opening up new markets for local food required the involvement of no fewer than six ministries: Education, Public Health, Economy, Local Government, Food/Environment, and Social Security. Implementation of the program is proving correspondingly difficult.

The Food Policy Alliance Cymru (FPAC), comprising researchers and practitioners concerned with the social and environmental impacts of food systems, formed in response to these and other challenges in Wales and beyond. Here we aim to demonstrate how, just as the fragmentation of food policy has had a number of negative effects for citizens, conversely the alignment of food-related policies can create synergies across government departments to achieve a wide range of policy targets relating to health and well-being, environmental sustainability, social justice, and community resilience. Within the Welsh context, the present development of a new Food (Wales) Bill is an opportunity to bring disparate food-related policies into alignment with a National Food Strategy and corresponding food system targets under the guidance of a Food Commissioner and commission. Similar challenges and opportunities arise in many national contexts as discussed, for example, in the United Nations Sustainable Development Goal 2: End hunger, achieve food security and improved nutrition and promote sustainable agriculture (United Nations, 2022).

We argue that moving food from the back seat to the driver's seat of policy development enables an integrated agenda of mitigating and adapting to climate change, restoring and maintaining biodiversity, supporting public health and equity, improving economic conditions and social ties, and strengthening national security through *food sovereignty*—enabling people and communities to have agency over how and what food is produced, traded and consumed and engage in the policy processes that shape the food system.

## Advancing agroecology

To achieve these goals, we propose a food policy approach rooted in *agroecology*. Agroecology is the science and practice of applying ecological principles to optimize the relationships between plants, animals, humans, and the environment, including the establishment and maintenance of a sustainable and fair food system. Through these relationships, agroecology supports food production, food sovereignty, and nutrition, while restoring the ecosystems and biodiversity that are essential for sustainable agriculture. This agroecological approach goes beyond minimizing harms to actively contribute to environmental and public health and economic resilience. These benefits are achieved through *place-specific* design and organization of farms, livestock, crops, and landscapes, drawing on unique local characteristics and conditions, and conserving cultural heritage and local knowledge.

While such approaches often build on and may seek to restore certain pre-industrial practices, they also leverage contemporary knowledge, technology, and connectivity to strengthen and support enduring food systems. Advanced understanding of soil science, ecosystem management, and climatology are employed to complement traditional practices. Processing facilities, transport networks, and renewable energy generation are strategically integrated with food production. Online connections are cultivated to facilitate collaborative networks and expand consumer education and access.

This agroecological approach is not merely theoretical: successes are already being demonstrated at the community scale. In Wales, a number of community "food hubs" have been supported by United Kingdom charities in order to facilitate cooperative relationships among local producers, distributors, and citizens. Some of these efforts focus on supplying publicly funded schools, colleges, care homes, and leisure facilities with locally grown food. Additionally, the "Our Food" initiative in the Brecon Beacons supports small farming enterprises that utilize environmentally sustainable practices in supplying in-person and online local markets. Malmo, Sweden's third largest city, offers another example. After 10 years of focus on local, organic procurement, more than 80% of fresh food provided within public institutions (e.g., hospitals, council buildings, and schools) comes from organic-certified farms in the city vicinity (WWF, 2012).

These community-scale efforts can bring a number of benefits including strengthening community ties, supporting ecologically sound farming practices, increasing local availability and consumption of fresh produce, educating youth and adults about nutrition and sustainable agriculture, and reducing waste through cooperative networks. However, in order to be effective and sustainable over the long term, community-scale efforts require linkage to broader national food systems. A comprehensive policy approach can incentivize, reward, and assist community-scale efforts that produce public benefit; incorporate worker protections along the full supply chain; pool and share knowledge, including assisting with network building and sharing best practices; and ensure that policies and regulatory approaches across all domains line up in support of sustainable food system goals including public and environmental health and economic development.

## Six-part framework for food systems priorities

We propose a six-part framework of strategies for food systems policy that can harness the benefits of agroecological approaches to support food systems that are equally strong in environmental, economic, social, and agronomic dimensions. Each of these strategies dovetail with and amplify one another.

## Strategy 1: Food for all

Beginning with the clear objective of producing and providing nutrition for all citizens sets the baseline for a "driver's seat" food policy. Pursuing *Food for All* requires a national strategy for assessing and optimizing capacity for food growing and processing as well as ensuring dignified access and affordability, including an adequate benefits and emergency support system. Upholding children's right to food (part of the UN Convention of the Rights of Child, Article 27) is a central element of this strategy. Another key feature of a Food for All strategy is providing access to land for interested citizens, households, and cooperatives to grow their own food.

## Strategy 2: Food for public health

Beyond the first objective of sustenance, pursuing *Food for Public Health* prioritizes producing and providing food that improves health status. In Wales, as in many industrialized countries, this involves recognizing low levels of consumption of fruits and vegetables (among the Welsh population, averaging 2.5 servings per day for those over 11 years of age; Food Foundation, 2021). Food for Public Health focuses on producing sufficient vegetables to meet individuals' daily requirements, facilitating consumption of fresh foods by shortening supply chains through community-scale production and distribution, and aligning economic incentives with the provision of highly nutritious foods rather than non-nutritive consumables such as ultra-high processed foods, sweets, and alcohol. This strategy also involves an education component, particularly in primary and secondary schools. Policies supporting Food for Public Health require careful consideration to avoid creating new hazards: for example, a sugar tax that does not address other types of sweetening additives can lead to increased consumption of artificial sweeteners with a number of deleterious health effects.

## Strategy 3: Net zero food system

Setting forth a *Net Zero* objective for the national food system provides a sturdy framework for orienting toward community-scale hubs that reduce transport emissions, emphasizing minimally processed foods, and shifting away from high levels of meat production. Key components of this strategy also include policies to reduce food waste and import policies that account for environmental impacts of imported foods at every point along the supply chain.

## Strategy 4: Farming for nature and climate

In addition to Net Zero goals, this strategy capitalizes on the capacity of food production to *improve* ecological conditions through agroecology. Through policies that support and incentivize practices that work in concert with nature such as inclusion of on-farm wildlife habitats, organic farming, plant diversity, crop rotation, and integration of livestock as natural composters and weed managers, *Farming for Nature and Climate* will restore ecosystem health and mitigate against climate change, both essential for present and future food production (Defra, 2021). These policies may also involve taking some lands out of the food production system to make space for nature-based solutions to tackle the nature and climate emergencies.

## Strategy 5: Sustainable seafood

Marine management policies for coastal countries are also integral to sustainable food systems. *Sustainable Seafood* policies not only address overfishing and destructive practices such as blasting and trawling but also tie together coastal development policies and management of waterways to reduce pollution and erosion affecting marine life. Putting in place effective monitoring technologies is an essential component of this strategy to document fishing activities and assess the health of aquatic ecosystems such as seagrasses, marshes, and coral reefs.

## Strategy 6: Sustainable food sector jobs and livelihoods

A final policy dimension crucial to a sustainable food system concerns the treatment of and protections for food sector workers. For a food system to function effectively in support of well-being, those who earn their living within the food system must be enabled to receive a living wage and fair return for their labor. *Sustainable Food Sector Jobs and Livelihoods* policies ensure that food sector work, whether on land or sea, is free from exploitative practices. This strategy goes beyond focusing on individual businesses or merely mandating higher wages to develop structures that support food sector work that is varied, engaging, and empowering, with ample opportunities for career advancement at all levels.

# Tools for food systems policy effectiveness

These six strategies cannot be pursued in isolation, as each component has implications for and effects on the other strategies. A driver's-seat food system policy will require a number of tactical approaches to ensure cohesion and effectiveness. We propose the following approaches as guiding principles for implementing the six-part framework.

## Audit

Developing a sustainable food systems policy begins with conducting comprehensive legislative, policy, infrastructure, land, and skills gap analyses. A comprehensive audit using the six-part framework can identify which existing policies and practices support or detract from the environmental, public health, social, and security goals reflected in the six strategies. For example, a city might consider what it currently provides in terms of healthy food access, particularly for those living in food deserts or lacking transportation to grocery stores; how it supports local food production through measures including urban agriculture, community gardens, and small-scale farming; how it supports sustainable food procurement through local and responsible producers; how it reduces food waste through measures such as composting, food recovery programs, and education campaigns; how it coordinates food policy across areas such as public health, transportation, and economic development; and how it builds resilience in the food system to shocks and disruptions such as natural disasters, pandemics, and economic downturns.

### Policy integration

In pursuing policy adjustment and development, discussions concerning food production, supply, and consumption should consider all six strategies, aiming to simultaneously support as many dimensions as possible and avoiding conflicting goals. The agroecological approach allows for food systems policy to concurrently address climate and ecological emergencies, public health crises, and food insecurity. Examples include farm support schemes that maintain and enhance resilient ecosystems while producing more healthy food close to consumers; public procurement of sustainable locally produced food for hospitals and school meals; and local cross-sector food partnerships to share knowledge and resources, shorten supply chains, and reduce waste.

### Investment

Public investment in the food system should reflect actual public costs and public benefits across all six strategies including health, environmental, and security risks and advantages. Examples include agricultural investment schemes to cover the true costs and public benefits of sustainable farming; capital grants to support short supply chain infrastructure (e.g., food hubs, small scale horticulture, and local processing facilities); investment in workers to develop the agroecological farming and production skill base; and public provision of healthy food in schools, hospitals, and other keystone institutions.

### Education

The public education system and community engagement efforts are essential tools for equipping citizens with the knowledge and skills to purchase, cook, and eat—and even grow—foods that support a healthy and sustainable diet. Education is also vital to developing the agroecological skills and knowledge base for work within a sustainable food system. Examples include integrating food skills in public education curricula at every level, embedding nutritional and food-growing skills courses in community programming, and developing apprenticeship schemes within sustainable food sector endeavors.

### Accountability and enforcement

Effective food systems policy must include compelling monitoring and enforcement mechanisms. Through transparent processes involving citizen and stakeholder engagement, policymakers should set, track, and share clear targets for each of the six strategies. These targets must be accompanied by effective enforcement mechanisms. For example, third-party certifications and labeling programs could be used to verify that food products meet certain standards or criteria such as organic or fair trade. Inspections and audits of food processing plants, farms, and restaurants could ensure compliance with food safety and other regulations. Penalties and sanctions for violations could result in fines, suspension or revocation of licenses or permits, or even criminal prosecution in extreme cases. Traceability and tracking systems, public reporting, and whistle-blower protections could further support transparency.

### Grassroots innovation

The place-specific nature of agroecology relies on locally distinct conditions, knowledge, and opportunities. Effective food systems policy should facilitate and capitalize on innovative approaches and new technologies emerging from local practice and experience. Examples include supporting farmer-led research; collaborating to drive more equitable resource distribution, for example through community grants to develop new business models; providing online platforms for peer-to-peer networks across the food system; and actively identifying and amplifying successful innovations to regenerate soils, improve animal welfare, and restore natural environments.

### Global responsibility

This final principle focuses on ensuring that policy decisions made at home do not negatively impact people or places abroad. To support sustainability over the long term, import policies must not displace environmental or social costs elsewhere. Examples include fair trade policies, ensuring food supply chains are deforestation-free, and withdrawing any procurement agreements that contribute to human exploitation.

## Conclusion

The food system has the potential to be a central lever in addressing present climate and nature emergencies, public health challenges, and issues of equity and accessibility. Whereas the past 50 years have seen increasingly unsustainable food system practices relying on vast global distribution networks, today local farmers, and communities are demonstrating the viability of nature- and climate-friendly small-scale production and supply chains and the positive impact of building relationships back into the food system. The six-part framework and implementation principles proposed here can support and link together community-scale efforts to establish food systems that simultaneously care for people and the planet. At the national scale, this agroecological approach can contribute to national security by establishing food sovereignty, which emphasizes ecologically appropriate and socially equitable production, distribution, and consumption as ways to sustainably and independently meet all citizens' basic need for nutritious food.

We note that an accessible first step in many settings is to begin with public procurement. As an initial move toward an integrated, driver's-seat food systems policy, decision makers can ensure that when public money is spent on food—for example in schools, hospitals, and government buildings—these purchases reflect national environmental, public health, and social objectives. Public procurement can set the bar and promote a transformation toward agroecological principles by procuring sustainably grown and raised, highly nutritious food from local growers and suppliers committed to fair labor practices. Assuring coherence between stated public and environmental health objectives and public spending on sustainable food production is an excellent step by which governments can demonstrate leadership in this critical area while also catalyzing the development of critical infrastructure.

A second, more complicated step could involve building and moderating localized communication platforms to better support collaboration among growers, food processing facilities (e.g., mills and abbatoirs), distribution channels, and direct-to-consumer sales. Such platforms could also incorporate locally collected and remotely sensed data on climatic, hydrological, and soil conditions along with population information and other indicators relevant to food supply and demand. Developing and maintaining these clearinghouses for collaboration and data sharing could help empower the development of local networks that can access relevant public and research knowledge through data dashboards and training in their interpretation and use. This move toward leveraging technological advances to facilitate local collaborations and democratize data avoids the nostalgic stance of trying to re-create a pre-industrial food system.

We acknowledge the difficulty of transforming systems that are deeply entrenched and largely controlled by multinational actors whose priorities may not align with long-term sustainability and local sovereignty. Equally, individual decision making is likely to be governed by short-term considerations and price signals. However, the climate crisis together with the data revolution present an unprecedented opportunity to shift policies and practices. With extreme weather events, sustained high temperatures, and depleted soils making conventional approaches less effective and more expensive, there is a growing willingness to explore alternatives even among large-scale producers, as seen for example in the switch of Oreo's parent company, Mondelēz, to sustainable cacao. At the same time, the increasing availability of agroecological data and rapidly advancing capability to process this data for projections and modeling can allow more decision makers to understand and visualize the consequences of sustainable vs. unsustainable practices. The growing global movement toward data sharing and transparency, for example through the work of the international Research Data Alliance, can be expected to further disrupt patterns of exploitation and manipulation that have long been hidden from public view.

Just as good food has the power to nurture the body, good food policy has the power to foster community cohesion, biodiverse ecosystems, and fair labor practices, resulting in resilient food systems delivering wellbeing objectives. There are many untapped opportunities to re-gear food policies to ensure they all move in the same direction of sustainability, including farm policies, rural development, planning, horticultural development, and trade and marketing. Now is a crucial time to build for the future, with the COVID-19 pandemic and the cost-of-living crisis exposing the vulnerabilities of current food systems reliant on foreign trade and underpaid labor. Designing more resilient, sustainable, and just food systems is a vital part of preventing future food crises and creating an enduring foundation of public and environmental health.

## Author contributions

Food Policy Alliance Cymru developed the ideas presented in the manuscript. EA and AS developed the framework for the manuscript. EA wrote a first draft of the manuscript based on previously written Food Policy Alliance Cymru materials where ideas were developed. Food Policy Alliance Cymru, EA, and AS all worked on subsequent versions of the manuscript until finalized. 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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# 2022 UK heatwave impacts on agrifood: implications for a climate-resilient food system

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Record-breaking high temperatures were experienced across the United Kingdom during summer 2022. The impacts of these extreme climatic conditions were felt across the food system, including increased energy costs for cold storage, the failure of refrigeration systems in numerous retail facilities, and impacts on livestock including heat stress. Future climate projections indicate an increased likelihood and duration of extreme high temperatures like those experienced in 2022. Learning from the impacts of the 2022 heatwave on the United Kingdom food system can help identify adaptations that build resilience to climate change. We explore the impacts through two case studies (United Kingdom poultry and wheat sectors), discuss potential adaptation options required for a climate-resilient, net-zero United Kingdom food system and consider future research needs. United Kingdom chicken meat production was 9% lower in July 2022 than July 2021; in contrast, energy costs increased for both production and refrigeration. Potential heatwave adaptation measures for poultry include transitioning to heat tolerant chicken breeds, lower stocking density, dehumidification cooling and misting systems, nutritional supplements, and improving retail refrigeration resilience and efficiency. United Kingdom wheat yields were 8% higher in 2022 than the 2017–2021 average. Increases were observed in every United Kingdom region but were least in the South and East where the heatwave intensity was strongest. Future adaptation measures to avoid negative impacts of summer heat stress on winter wheat could include earlier maturing and heat/drought tolerant varieties, earlier autumn sowing, targeted irrigation for drought around anthesis, and soil and water conservation measures.

KEYWORDS

**heatwave, agriculture, food, poultry, wheat, adaptation, climate change, resilience**

## 1 Introduction

Weather and climate extremes have wide-ranging impacts throughout the UK food system (Falloon et al., 2022) and are one of its highest-risk future shocks (Betts et al., 2021). High temperatures cause heat stress to crops, livestock and workforces (Falloon and Betts, 2010; GFS, 2014; Falloon et al., 2015). The hot, dry summers of 2018 and 2020 reduced UK crop yields (Committee on Climate Change, 2018; Berry and Brown, 2021), while high summer temperatures

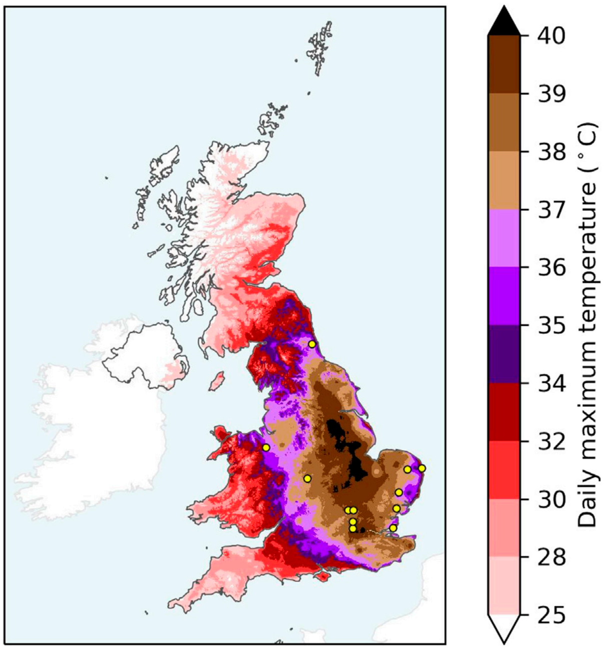


FIGURE 1
UK maximum temperatures on 19 July 2022 (HadUK-Grid 1 km data; Hollis et al., 2018); yellow dots represent supermarket stores that experienced refrigeration system issues during the summer 2022 heatwave.

reduce the quality of fruits, brassicas, and tomatoes (Committee on Climate Change, 2018). This can increase supply variability across the food chain which is compounded by a simultaneous increase in consumer demand for barbecue food, salads, and fresh fruit. High temperatures increase food spoilage and safety risks (Bezner-Kerr et al., 2022), demanding different handling, storage and transport practices including increased cold chain use (James and James, 2010).

2022 was a record warm year in the UK observational record since 1884, the first year with an annual mean temperature above 10°C, and the seventh sunniest year since 1910 (Kendon M. et al., 2023a). 2022 rainfall was 6% below the 1991–2020 average, with January-August 2022 being the driest across southern England since 1976, and equal-sixth driest since 1836 (Kendon M. et al., 2023a). The unprecedented 18th-19th July heatwave (Kendon M. et al., 2023a) exceeded previous records, with the highest temperatures occurring in the East of the UK, including temperatures above 40°C for the first time on records (Figure 1).

The impacts of these extreme conditions were felt across the UK food system including:

- Increased energy costs for cold storage[1] and refrigeration systems failure in retail facilities[2]
- Yield losses in fruits and vegetables[3]
- Increased livestock heat stress (Cooke and Rivero, 2023)
- Limited availability of grass forage for livestock

Human influence has already increased the chance of the UK experiencing temperatures above 40°C, relative to the pre-industrial period (Christidis et al., 2020). Future projections indicate an increasing likelihood and duration of extreme high temperatures at least as severe as those experienced in 2022. By the 2070s under a high emissions scenario, hot summer days increase by 3.8°C–6.8°C, along with a large increase in the frequency of hot spells (Met Office, 2021; Met Office, 2022). The intensity of summer rainfall events is expected to increase, but summers are projected to be drier overall with an increased severity of multi-season droughts (Hanlon et al., 2021).

The UK agri-food sector contributed £116.2 billion (6%) to national Gross Value Added in 2020 (Department for Environment Food and Rural Affairs, 2023a), and poultry meat and wheat production were worth £3.1 billion and £4.1 billion in 2022, respectively (Department for Environment Food and Rural Affairs, 2023b). We focus on the impacts of the 2022 UK summer heatwave using two case studies: poultry and wheat. We explore potential adaptations to manage the effects of future heatwaves, contributing to a climate-resilient, net-zero UK food system.

## 2 Poultry sector

### 2.1 Heatwave impacts

The impacts of the summer 2022 heatwave were experienced throughout the UK poultry industry supply chain, markedly in broiler farms and retail facilities.

In July 2022, the production of chicken meat by volume in the UK experienced a 9.2% reduction compared to July 2021 (a 2.6% reduction from the 1997–2022 July average, for which the year-to-year standard deviation is 5.6%; Department for Environment Food and Rural Affairs, 2022a). Greater damages were experienced in the East of the UK, which was exposed to the highest temperatures (Figure 1). Animal welfare-reported incidents of heat stress and dead-on-arrival (DOA) at slaughterhouses[4] were impacted in July and August 2022, while over 18,500 chickens died in transport due to heat stress—compared to 325 deaths in the same period in 2021[5].

Poultry meat production is highly energy intensive due to the demand for heating/cooling and lighting (Tsolakis et al., 2018). Retail stores in Eastern UK experienced the strongest impacts. One supermarket experienced issues in the refrigeration systems of 12 stores (Figure 1), while its energy consumption increased to ~4 GWh above the expected summer value[6]. Electricity

1 https://www.foodmanufacture.co.uk/Article/2022/08/15/Extreme-weather-ravaging-the-UK-challenges-food-industry.

2 Personal communication—Chris Brown, Asda.

3 https://www.theguardian.com/environment/2022/aug/01/uk-farmers-count-cost-as-heatwave-kills-fruit-and-vegetable-crops.

4 https://www.food.gov.uk/board-papers/fsa-22-09-18-annual-animal-welfare-main-report-202122.

5 https://www.carbonbrief.org/revealed-thousands-of-chickens-in-transit-died-from-heat-stress-on-day-uk-hit-40c/.

6 Personal communication—Chris Brown, Asda.

**TABLE 1** 2022 wheat yields for UK regions, percentage difference relative to the 2017–2021 average yield for each region. Data source: Department for Environment Food and Rural Affairs (2022b).

| Region | 2022 wheat yield (%) difference relative to 2017–2021 average) |
|---|---|
| UK | 8.1 |
| North East | 8.6 |
| North West | 10.9 |
| Yorkshire | 11.2 |
| East Midlands | 10.2 |
| West Midlands | 10.6 |
| Eastern | 3.3 |
| South East | 6.5 |
| South West | 8.8 |
| Wales | 10.1 |
| Scotland | 14.6 |

consumption on 19th July 2022 was ~20% higher than the average daily summer consumption.

## 2.2 Potential adaptation measures

Currently, the most farmed breeds are selected for large breast size (~40% total body mass), while heat resistant breeds have smaller breast size (~35% total body mass). Changing to more heat tolerant breeds such as the Orpington (Cheng, 2010; Li et al., 2013; Fu et al., 2016) could reduce heat stress-related mortality rates. Even accounting for decreased breast size, this could provide a net economic benefit during heatwaves (Sun et al., 2021). Changes in nutrition (e.g., vitamins and feed additives) can mitigate some heat stress impacts but evidence is conflicting regarding their efficacy (Supplementary Table S1).

Broiler housing can be altered to decrease heatwave impacts using misting systems and ventilation (Department for Environment Food and Rural Affairs, 2018). Misting systems are the least expensive method requiring little alteration, but their utility in reducing heat stress is limited since they increase humidity (Khalifa et al., 2018). These issues may be reduced using maximized air flow and/or alternative dehumidification cooling systems to reduce relative humidity levels (Aleem et al., 2022) and overall heat stress impacts.

Lower stocking densities can improve breast meat quality and relieve oxidative stress from high temperatures (Son et al., 2022), with no upfront cost. The impacts of heat stress on poultry during transport (Davie et al., 2021) could be reduced by increasing air-conditioning, increasing airflow and night-time transport (Falloon et al., 2023).

Installing protective systems could prevent existing electricity networks that support refrigeration from collapsing during a heatwave. Auto load shedding switches off selected components at peak demand, preventing power blackouts (Ahsan et al., 2012) but reduces refrigeration capacity.

# 3 Wheat sector

## 3.1 Heatwave impacts

In contrast to impacts on poultry in 2022, UK winter wheat production was not adversely affected. 2022 wheat yields were 8% higher than the 2017–2021 average, with increases in every UK region[7] (Table 1). The 2022 yield increases were greater in Northern/Western regions of the UK, and least in the South/East where the intensity of the heatwave was strongest. Under long-term climate scenarios, a similar South/East-North/West gradient of wheat yield changes (Cho et al., 2012) and variability (Putelat et al., 2021) has been noted. While high temperatures and drought can negatively impact wheat production (e.g., Machado and Paulsen, 2001; Farooq et al., 2011; 2014; Barlow et al., 2015) the magnitude of impacts depend on the severity of the hazard and the wheat growth stages during which they occur.

Hotter, drier summers will be more common in the future due to climate change (Met Office, 2022). Understanding the reasons for the higher 2022 wheat yields, despite these conditions, and whether the benefits might be maintained during multi-year hot and dry periods will help underpin future wheat resilience by informing farming adaptations and the development of new varieties.

### 3.1.1 Temperature

Heat adversely affects wheat yield and quality via prolonged (weeks-months) periods of above optimum temperatures, or short periods (~1–3 days) of very high temperatures above approximately 35°C (e.g., Harkness et al., 2020). The impacts are greatest in the 2 weeks leading to anthesis (flowering) and grain filling, impacting on grain number and weight respectively (Farooq et al., 2011; Barlow

7 https://www.gov.uk/government/statistics/cereal-and-oilseed-rape-production/cereal-and-oilseed-production-in-the-united-kingdom-2022. Note that 2022 yield data for Northern Ireland are not available.

et al., 2015). Impacts on grain filling are most significant in the early stages of this process.

The warm temperatures were distributed unevenly throughout the summer, with anomalies of 0.5°C, 1.3°C, and 1.5°C above the 1991–2020 averages for June, July, and August, respectively (Kendon M. et al., 2023a). There were two significant heatwaves in mid-July and mid-August. UK crop development reports[8] for 2022 suggest that anthesis occurred, as normal, around the end of May and early June, with most winter wheat being in growth stage 71 out of 99 (flowering occurs at stage 61). The most critical period of vulnerability to heat stress for most UK winter wheat was late May to early July 2022 when temperatures were above the long-term mean, but there were no significant heat shocks. The exceptionally warm conditions occurred too late in the crop lifecycle to have a significant impact. Winter wheat harvesting[9] began during the second week of July and was largely complete by the end of August, associated with the extended warm period during 2022.

### 3.1.2 Drought

Drought stress primarily affects wheat yields during the reproductive period (Harkness et al., 2020)—in the two-week window before and including anthesis via reduced grain numbers, and after anthesis via a reduction in grain filling which negatively impacts grain weight. Severe crop growth reduction can occur if the entire growing season experiences water stress (Harkness et al., 2020).

Summer 2022 was dry for the UK, receiving 64% of average rainfall versus the 1991–2020 baseline, ranking in the lower third of all years since 1836. Rainfall was not evenly distributed throughout the summer. May, June, July and August recorded 109%, 80%, 59% and 60% of rainfall relative to 1991–2020 respectively. Dry spells occurred in mid-to-late January, late March and April, July, and early August 2022. Crucially, May to early July did not experience significant prolonged dry spells (Kendon M. et al., 2023a).

It appears there was sufficient rainfall during the period when winter wheat is particularly vulnerable to avoid significant yield impacts. The winter and spring dry spells may not have been significant enough to impact crop development, perhaps due to sufficient subsoil water from 2021 rainfall being available for crop growth. Access to subsoil water would have increased resilience to the July-August dry spells when grain filling was taking place but cannot be guaranteed in multi-year hot and dry periods.

## 3.2 Potential adaptation measures

The 2022 heatwave illustrated that high temperatures may not necessarily have detrimental impacts on winter wheat yields, depending on their timing during the growing season. The regional statistics (Table 1) hint at the potential for adverse impacts in more severe conditions, with smaller yield increases in regions experiencing higher temperatures. This suggests several potential adaptation strategies. Growing earlier maturing varieties would allow anthesis to occur earlier and avoid greater risks from high temperatures, while earlier autumn sowing (Cho et al., 2012) could allow crops longer development time. Putelat et al. (2021) suggest that future wheat crops may escape heat (and drought) impacts through faster development because of warmer year-round temperatures. High temperature impacts could be mitigated by targeted breeding for deeper root systems combined with lower metabolic costs (Li et al., 2022), water storage and irrigation for drought around anthesis, or soil conservation and improvement measures to increase water and nutrient retention. The winter wheat varieties grown in the UK are photoperiod sensitive varieties and require a vernalization period (Sheehan and Bentley, 2021). Earlier planting dates may put crops at greater risk of disease and frost damage during winter. These factors will need to be considered when choosing appropriate adaptation options.

## 4 Discussion

UK-wide increases in the average number of days per year when livestock heat stress thresholds are exceeded are anticipated (Supplementary Figure S1). This suggests a clear need for effective large-scale adaptation. Adaptation measures for poultry production include transitioning to heat resistant breeds, changing nutritional intake, reducing stocking densities, and improving ventilation and misting systems in poultry housing. At the retail and consumer end, increasing heatwave frequency and intensity will put pressure on refrigeration systems, increasing energy costs and system failures. Efficiency improvements and installation of protective systems for power supply to refrigeration systems could reduce heatwave vulnerability in retail facilities.

The above average wheat yields reported in 2022 support studies that suggest climate change may have different impacts on UK wheat depending on where it is grown (e.g., Harkness et al., 2020; Jägermeyr et al., 2021; Putelat et al., 2021). Wheat is vulnerable to extreme heat and drought in late spring or early summer. The increasing likelihood of these conditions under future climates, particularly in the South/East of England, suggests that inter-annual and spatial yield variability may increase in the absence of effective adaptation such as better water management and heat and drought tolerant varieties.

## 4.1 Barriers to adaptation measures

Current UK wheat varieties are bred for high grain yield. Moving to more heat (or drought) resilient crops may require trade-offs, whereby resilient varieties perform well during stress conditions, but less well than current varieties during 'normal' conditions. For poultry breeds, there will be a trade-off between meat quantity per bird and resilience during heatwaves. Further research is required to understand the longer-term production and economic implications of such trade-offs.

Current challenges to the UK poultry sector (e.g., avian influenza and economics) mean that widespread transition may only be feasible with additional support. All farmers are eligible for the UK government's 'Basic Payment Scheme (BPS)' (Department for

8 https://ahdb.org.uk/cereals-oilseeds/crop-development-report.

9 https://ahdb.org.uk/cereals-oilseeds/gb-harvest-progress.

Environment Food and Rural Affairs, 2019; Rural Payments Agency, 2022), but poultry farmers are currently ineligible for further subsidies. In addition, at least 5 ha of eligible land are required to receive the BPS while approximately 45% of specialist poultry farmers in England have less than this amount (Department for Environment Food and Rural Affairs, 2023c). Financial barriers could impact the uptake of proposed adaptation options, both for poultry and winter wheat. For the refrigeration systems of retail facilities, retrofitting one technique or complete system replacement come at high initial costs. The longer-term economic outcomes therefore need to be assessed, and priority should be given to stores in the most vulnerable regions. Changing poultry breeds or reducing stocking densities may have smaller financial impacts during heatwave conditions. The financial implications of planting earlier maturing and heat/drought tolerant wheat varieties is uncertain and will depend on the balance between lower production during 'normal' years and seasons experiencing significant heat impacts. Improved soil and water conservation measures are unlikely to incur significant additional costs, while implementing targeted irrigation would be a significant change for the UK wheat sector.

Seasonal forecasts could support adaptation decision making in the agrifood sector (Falloon et al., 2023), but their usefulness for heatwave resilience in the poultry and wheat sectors will depend on several factors. The timescales of decision making will impact whether effective action can be taken—in wheat farming many decisions relevant to high temperature impacts (e.g., sowing dates, varieties planted) are made the year before harvest, so opportunities to take a different course of action may be limited. The skill of seasonal forecasts is limited during the UK growing season (Falloon et al., 2018), and trust (Pope et al., 2017), user-relevance, and experience with probabilistic information also affect uptake.

Large-scale implementation of effective adaptation measures requires consideration of which actors should drive, fund and facilitate it—which will impact how the risks at different scales (e.g., individual farmers, processors, retailers, or overall UK food security) are balanced.

## 4.2 Implications of adaptation measures for net zero

The refrigerants used in common hydrofluorocarbon (HFC) refrigeration systems, R404A and R407A, have global warming potentials (GWP) of 3,943 and 2,107, respectively (Mota-Babiloni et al., ¸ 2015; Acha et al., 2016; Gao et al., 2022). With annual leak rates up-to 30%, HFC systems release greenhouse gases that deplete stratospheric ozone (Besher et al., 2015). $CO_2$ has a much lower GWP than HFC, so is the preferred refrigerant for retail in terms of net zero goals (Santosa et al., 2018; Dilshad et al., 2019; Efstratiadi et al., 2019; Yu et al., 2019). However, $CO_2$-based systems are less efficient than HFC systems in hot climates (Fricke et al., 2019), implying a trade-off between the implications for net zero goals and climate mitigation, and for climate adaptation. Performance enhancement technologies for $CO_2$-based systems could improve their high-temperature efficiency (Ge and Tassou, 2009), and contribute to emissions reductions. Increasing poultry housing ventilation and misting and implementing transport measures to mitigate heatwave impacts could conflict with net zero goals by increasing energy consumption (which increases during high temperatures due to lower efficiency) and greenhouse gas emissions (Falloon et al., 2022).

Changing wheat varieties and sowing dates are likely to have negligible impacts on GHG emissions or carbon storage, while irrigation could incur additional energy costs via pumping, and soil and water conservation measures could potentially improve net zero outcomes through increased soil carbon storage and reduced soil carbon losses (e.g., Page et al., 2020).

## 4.3 Future research needs

The 2022 UK heatwave illustrates the complexity of the impacts of extreme events on the agrifood system; future research should aim to provide detailed studies of them, the resulting needs for adaptation and implications for net-zero goals. A better understanding of the interactions between the timing of extreme weather events and management decisions across the whole food chain could support better resilience. For example, how do antecedent conditions affect impacts, and how do differences in operational decisions affect the overall outcome?

A key challenge for food system resilience is the availability of data to support research studies, and development and evaluation of models and tools (Falloon et al., 2022), both within the food chain, and of local meteorological conditions. Examples include the lack of robust, detailed, public data on poultry mortality and welfare in housing and transport, but also across the broader food chain (e.g., consumer trends, energy use, storage and transport practices/impacts, food safety aspects and workforce heat stress). There is also a lack of readily available, detailed crop yield data in the UK that would support impacts and adaptation assessments, and the development and application of models.

Further research is needed to quantify the effectiveness of adaptation options, both individually and in combination, and to provide cost-benefit analyses. Further research is needed to develop optimum winter wheat varieties for the future UK climate, considering the expected occurrence of extreme events, the potential for compound events and multi-year drought, and vernalisation requirements. In addition, the effectiveness of broader range of adaptation options should be assessed, including diversification and alternative cropping systems.

There is a need to build on experience gained during extreme weather events to help avoid 'knee-jerk' responses and maladaptation. For example, for very heavy rainfall events future changes are not expected to unfold as a smooth trend and could be experienced as clusters of record-breaking events followed by decades with none (Kendon E. J. et al., 2023b). Therefore, costly short-term decisions taken to adapt to an experienced weather shock may not prove cost-effective in the mid-term. The timing of extreme events and weather patterns are critical to food system impacts—for example, 2023 UK wheat yields and quality were negatively impacted by high rainfall. In addition, given the projected increases in both the frequency and severity of extreme weather events towards the end of this century, greater levels of adaptation will be needed in the long-term to maintain resilience.

Improvements in seasonal forecasting to support agricultural decision making (e.g., Falloon et al., 2018) would help farmers choose appropriate varieties for upcoming seasons and prepare adaptations to farming practices in advance; there is also potential for long-range forecasts to support decision-making across the broader food chain (Falloon et al., 2022). Further developments to process-based models and statistical/machine learning models of wheat yield (e.g., Shirley et al., 2020) will be valuable in identifying indirect impacts on yields (e.g., farming practices and pest and disease pressures).

## Data availability statement

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

## Author contributions

JD: Supervision, Writing–original draft, Writing–review and editing, Conceptualization, Investigation. PF: Conceptualization, Writing–original draft, Writing–review and editing, Supervision. DP: Conceptualization, Investigation, Writing–original draft, Writing–review and editing. TS: Conceptualization, Investigation, Writing–original draft, Writing–review and editing. MH: Conceptualization, Investigation, Writing–original draft, Writing–review and editing. TW: Conceptualization, Investigation, Writing–original draft, Writing–review and editing. TL: Conceptualization, Investigation, Writing–original draft, Writing–review and editing. EG: Conceptualization, Investigation, Writing–original draft, Writing–review and editing. JeS: Conceptualization, Investigation, Writing–original draft, Writing–review and editing. JaS: Conceptualization, Investigation, Writing–original draft, Writing–review and editing. TC: Conceptualization, Writing–original draft, Writing–review and editing. AC: Conceptualization, Writing–original draft, Writing–review and editing. EP: Conceptualization, Writing–original draft, Writing–review and editing. SG: Conceptualization, Writing–original draft, Writing–review and 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.

The reviewer KT declared a past collaboration with the author PF to the handling editor.

The authors declared that they were an editorial board member of Frontiers, at the time of submission. This had no impact on the peer review process and the final decision.

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## Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2023.1282284/full#supplementary-material

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# Managing climatic risks in rice–wheat cropping system for enhanced productivity in middle Gangetic plains of India

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Rice followed by wheat is the dominant cropping system in the middle Indo-Gangetic plains (IGP). Lower productivity (4.8 t $ha^{-1}$) of this cropping system in Bihar, compared to the national average (6.8 t $ha^{-1}$) due to several climate- and production-related issues, is a matter of concern for the farmers and the policymakers. Keeping all these in view, an experiment with rice–wheat cropping system was carried out during 2020–21 and 2021–22 in 17 adopted villages of 13 districts of Bihar under the Project "Climate Resilient Agriculture Program (CRAP)" to evaluate the feasibility of early transplanting of rice in the month of June with the aim of achieving higher system productivity by early harvesting of rice and subsequent timely sowing of wheat before 15 November with the provision of assured irrigation. In this study, the concept of an innovative community irrigation approach and single-phase 3-hp submersible pump was employed. Long-duration rice variety (150 days) Rajendra Mahsuri-1 was sown during 20–25 May in the nursery and transplanted through puddling operation during 15–20 June in 17 locations. Under delayed conditions, the nursery sowing and transplanting window were 10–15 June and 10–15 July, respectively. Timely sown rice grown with the provision of a community irrigation system achieved a grain yield of 5.2 t ha$^{-1}$ and 85.8% higher water productivity, compared to late-sown crops. Following the harvest of rice, the HD-2967 variety of wheat was planted in the first fortnight of November and harvested in the first week of April, yielding 4.9 t ha$^{-1}$ with the application of 2–3 irrigations based on soil type and evaporative demand. Timely harvesting of wheat facilitated farmers of the region to take an additional crop of summer green gram. With an assured irrigation system and shifting planting dates and thereby managing climatic risks, the overall productivity of the rice–wheat cropping system was achieved to the tune of 10.1 t ha$^{-1}$ with a cropping intensity of 300% for better adaptation and sustainable production.

KEYWORDS

**rice–wheat, climate resilience, assured irrigation, risk management, adaptation**

## 1 Introduction

Rice–wheat cropping system (RWCS) is the most prevalent agricultural production system covering nearly 14 million hectares in the Indo-Gangetic Plains (IGP) of South Asia (Alam et al., 2016), of which 10 million hectares lies in India alone. This cropping system is predominantly followed in the states of Punjab, Haryana, Bihar, Uttar Pradesh, and Madhya Pradesh contributing around 75% of the national food grain production. However, the sustainability of RWCS in India is facing severe challenges mainly due to resource paucity (Jat et al., 2018; Mondal et al., 2020), water scarcity (Bhatt et al., 2016), and climatic variability (Jain et al., 2014). In the state of Bihar located in the middle IGP, the major food demand is met through RWCS, which contributes about 77.4% of the total food grain production from around 70% of the gross cropped area, but the productivity of both crops is very low due to the frequent occurrence of climatic stresses such as abnormal temperature, erratic rainfall, increased frequency and duration of dry spells, and early withdrawal and erratic nature of monsoon, which adversely affects the production potential and food security (Lal, 2019; Arunrat et al., 2020). The mean productivity of rice in Bihar stands at 2.5 t ha$^{-1}$, that too, with a decreasing compound agricultural growth rate of (−) 3.61% in 2017–2018, as compared to 2014–2015 (Economic Survey of Bihar, 2019–2020).

In Bihar such as in all other states of eastern India, the major constraint in getting the potential yield of rice is late transplanting (Sattar et al., 2017) due to delays in obtaining water for puddling operations following the late onset of monsoon on many occasions and the lack of irrigation facility at an affordable rate. There should be ponded water in the initial stage of transplanting for the smooth recovery of plants. For ensuring timely sowing and transplanting of rice, the major source of irrigation is groundwater, which is extracted by a diesel pump set. The diesel pump sets have centrifugal pumps, and they are not able to extract groundwater during peak hours in summer when the water table goes down and there is a great rush for transplanting. Diesel pump sets have high diesel consumption with comparatively lesser water discharge and higher greenhouse gas emission. In view of this, the government recently started electrifying the irrigation system with the installation of three-phase 5/7.5 hp. diesel pumps. These pumps operated by the farmers do not perform well as it requires a constant supply of electricity in all three phases. Moreover, the electricity consumption is almost 5 times per hour, compared to a 3-hp single-phase tube well. Accordingly, it requires an investment of significant funds. Considering the cost of irrigation, it is around INR 6000.00 per hectare for a diesel pump set, INR 3000.00 per hectare for a three-phase electrified irrigation system, and INR 300.00 per hectare for a 3-hp single-phase pump set. Hence, the high cost of irrigation coupled with the late onset of monsoon is also a major factor that compels the farmers of the region for late transplanting of rice. Consequently, late transplanting tends to significantly impact the occurrence of critical phenological stages of the crop. Under delayed transplanting, the flowering of the crop coincides with the prevalence of low temperatures beyond September. Under such a situation, there is a greater possibility that a large percentage of chaffy grains would be produced. Not only this but also the delay in transplanting affects the sowing of succeeding wheat crops. In this region, when wheat is sown beyond November, the problem of terminal heat stress during the flowering to the milking stage of the crop arises in most of the years and consequently, it affects grain setting and wheat productivity significantly. About 80% of wheat sowing is delayed in the region beyond the period of 25 November, forcing the crop to encounter higher temperatures (terminal heat) during the growing season (end of February to March) (Sattar et al., 2023). Therefore, terminal heat stress associated with dry westerly wind is a serious climatic constraint for successful wheat cultivation in India, particularly when it occurs during the grain-filling stage (Sandhu et al., 2016; Sattar et al., 2020). In one study on wheat, Poudel et al. (2021) observed that the optimum temperature during the anthesis and grain-filling stage ranges from 12 to 22°C. As evident, among all the weather factors, temperature plays a crucial role in determining the sowing time and consequently the duration of different phenophases, which ultimately affect crop productivity. Moreover, when the farmers go for delayed sowing (beyond 25 November), there is always a greater chance that the crop will face the fury of a hailstorm during the ripening and harvesting stage in the month of April as the region experiences a greater probability (>70%) of hailstorms during this month.

Participatory rural appraisal (PRA) provides an opportunity to analyze the livelihood issues of the farmers and helps scientists to understand the problems. It is an important tool to identify the location-specific researchable issues and find out possible short- and long-term benefits. Kumari et al. (2019) used the PRA tool in some districts of Bihar to develop problem-solution tree of the issues faced by the farmers. The climatic issues affecting rice–wheat production in the region were reported by Srivastava et al. (2018). In the present study, the PRA tool was used to address the problems faced by the farmers of rice–wheat cropping system, and based on this, villages in different districts were selected for this study.

Considering the above facts, the present study was undertaken to evaluate the feasibility of early transplanting of rice through an assured irrigation system and its impact on phenology, yield, and yield attributes. Early transplanting of rice ensured its early harvesting and timely sowing of subsequent wheat crops. Accordingly, the yield potential of RWCS by advancing planting dates and water productivity of rice under timely and late transplanted conditions were evaluated by employing an innovative approach through the Climate Resilient Agriculture (CRA) Program for higher system productivity, better adaptation, and sustainability under changing climatic scenarios. The innovation in this case refers to the early transplanting of rice through assured community irrigation by a 3-hp single-phase tube well.

# 2 Materials and methods

## 2.1 Study area

Bihar is located in the middle Gangetic Plains of India. The study was conducted in 17 different adopted villages of different Farm Science Centres (Popularly known as Krishi Vigyan Kendras, KVKs) of Dr. Rajendra Prasad Central Agricultural University, Pusa, namely, (1) Sukhet (Madhubani), (2) Jale (Darbhanga), (3) Manjhi (Saran), (4) Bhagwanpur Hat (Siwan), (5) Sipaya (Gopalganj), (6) Sheohar, (7) Sitamarhi, (8) Madhopur (West Champaran), (9) Narkatiaganj (West Champaran), (10) Parsauni (East Champaran), (11) Piprakothi (East Champaran), (12) Lada (Samastipur), (13) Birauli (Samastipur), (14) Vaishali, (15) Turki (Muzaffarpur), (16) Saraiya (Muzaffarpur), and (17) Khodabanpur (Begusarai), under the Project "Climate Resilient Agriculture (CRA) Program" funded by the Government of Bihar, India, during *kharif* seasons of 2020 and 2021, *rabi* seasons of 2020–2021 and 2021–2022, and summer seasons of 2021 and 2022. The location of the study area is given in Figure 1. The depth of the water table in the study area varies from 2 to 5 m below ground level (Anon, 2022).

## 2.2 Climate, soil, and cropping system

The region has a sub-humid subtropical monsoon climate. About 85% of the annual rainfall occurs during the monsoon season. Considering the cropping season, it is known as *kharif* season, during which rice crop is grown. The region experiences four seasons, *viz.*, Summer (March–May), Monsoon (June–September), Post-Monsoon (October–November), and Winter (December–February). The average annual rainfall of the region ranges from 1,230 to 1,400 mm. The month-wise rainfall distribution pattern is given in Figure 2. May is the warmest summer month of the year with a daily maximum temperature of 37–41°C, while the coldest winter month is January with a daily minimum temperature of 5–8°C in January (Bal et al., 2023). Although December, January, and February are the main winter months, temperature decreases significantly from November. The average temperature falls appreciably from 26.9°C in October to 21.9°C in November.

Soils of the study area are mainly young alluvium, calcareous, and predominantly sandy loam to loamy in texture. Soils are deep having calcium carbonate more than 10%. The water holding capacity varies from moderate to high. It has moderate drainage behavior. There is a wide variation in the nitrogen and available potassium status of these soils. Soil pH varies from 6.5 to 8.4. Rice–wheat is the major cropping system of the region and comprises about 60% of all crops and cropping sequences followed by the farmers (Kumari et al., 2022).

## 2.3 Methodology

### 2.3.1 Field criteria adopted for the study

The villages were selected through the Participatory Rural Appraisal Survey. In this region, late sowing and transplanting of rice are a usual practice due to the lack of affordable irrigation facilities and farmers' dependency on monsoon rains both for transplanting and for meeting further irrigation requirements during its growing period (Najmuddin et al., 2018). While selecting the villages, it was kept in mind that wheat sowing gets delayed in the area due to late harvesting of paddy, thus forcing the crop to be affected by terminal heat stress. In addition, another criterion was that the successive green gram crop was either non-productive or non-remunerative due to the late harvesting of wheat in these villages. In case of late harvesting of wheat following late planting, subsequent summer green gram is affected on many occasions due to the initial burst of pre-monsoon showers and monsoon rains, leading to crop damage. An area of 15 acres was selected in each of 17 villages, and one 4-inch tube well fitted with a 3-hp single-phase submersible pump was installed with a discharge capacity of 7–9 lps and irrigation command capacity of 15–20 acres each costing around 1.6 lakhs. While comparing the cost with a 15-hp three-phase tube well, it comes to around 17 lakhs per tube well. Moreover, these pumps do not perform well due to voltage fluctuations. It has a higher discharge rate as compared to the water demand of crops, it causes losses in irrigation water, and consequently, low water use efficiency is observed when compared with a 3-hp single-phase tube well. A group of 10–20 farmers from each village was formed with an agreement that all participating farmers will have an equal right and equal opportunity to avail irrigation facility as and when needed by the crop. One rural youth of the same adopted village was given the task of scheduling irrigation with a nominal cost of INR

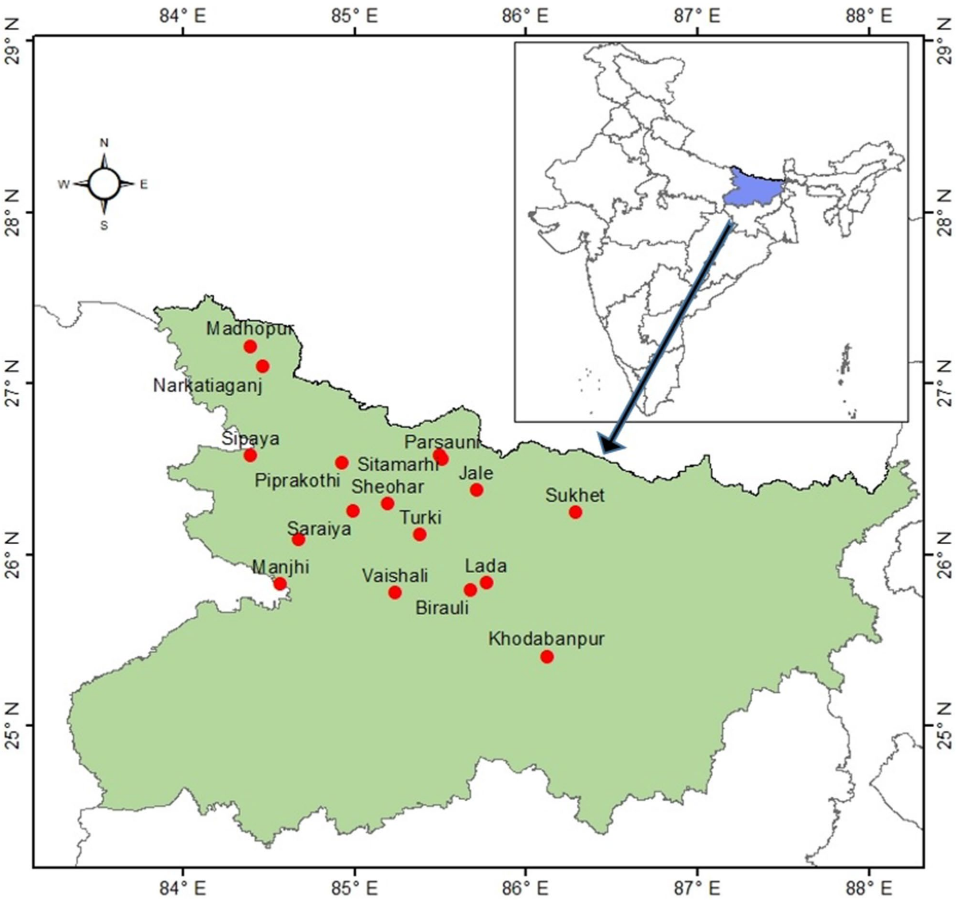


FIGURE 1
Location of the study area.

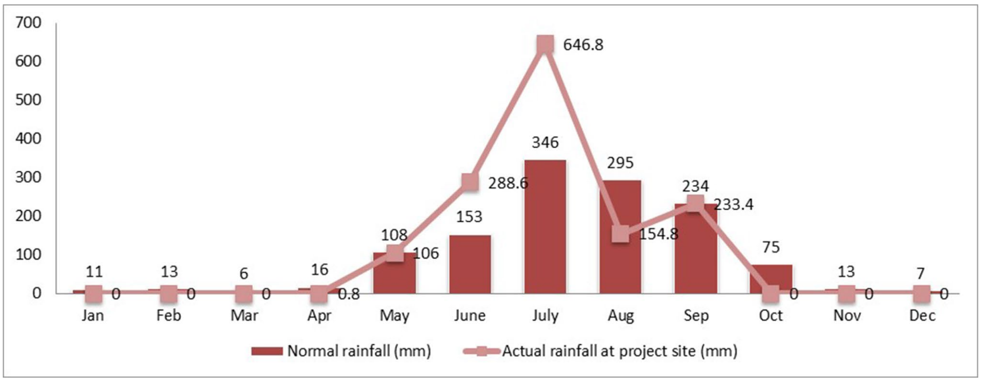


FIGURE 2
Comparative distribution pattern of normal rainfall (mm) and actual rainfall over the study area.

15 per hour. The amount, thus collected, was deposited in a revolving account for future management of the tube wells, operational cost, and honorarium for the youth facilitator.

Long-duration high-yielding rice variety (Rajendra Mahsuri-1) of 150-day duration was sown on 20–25 May in the nursery and transplanted on 15–20 June after puddling. In total, 2–3 irrigations were applied to the crop to maintain soil moisture above field capacity. Scheduling of irrigation was based on the disappearance of standing water from the crop field, and it was ensured that cracking in the rice field does not develop. The same variety of rice was sown during 10–15 June in the nursery and transplanted during 10–15 July, which is generally practiced by the farmers near the experimental plots. After the harvest of paddy, HD-2967 variety of wheat was sown on 7 November, and 2–3 irrigations were provided as per soil type and physiological demand of the crop. The same variety of wheat was sown during 25–30 November (regarded as delayed sowing) after the harvest of paddy crops during 15–20 November. The third crop of green gram was sown on 10 and 25 April, respectively, at different locations. All the agronomic parameters and yield attributing characters were studied, recorded, and analyzed.

Nitrogen, phosphorus, and potassium were applied to the rice crop in the ratio of 120:60:40. During the growing period of the crop, 50% of nitrogen and full doses of phosphorus and potassium were used as basal application. The remaining nitrogen was applied in two equal splits: one at tillering and another at the panicle initiation stage. For weed management, two hand weedings were done at 30 and 60 days after transplanting. In the case of wheat, nitrogen, phosphorus, and potassium at 120, 60, and 40 kg $ha^{-1}$ were applied. All the phosphorus and potassium and half dose of nitrogen were applied at sowing as basal dose. The remaining half dose of nitrogen was top dressed in two equal splits at crown root initiation and boot stages.

### 2.3.2 Calculation of water productivity

Crop water productivity, irrigation water productivity, and effective rainfall were calculated using standard methodologies. Renfro equation as quoted by Chow (1964) has been employed in this study to work out effective rainfall as follows:

$$\mathrm{Re} = \left(\mathrm{E}^{*}\mathrm{Rg}\right) + \mathrm{A}$$

where Re is effective rainfall, Rg is growing season rainfall, A is average irrigation application, and E is the ratio of consumptive use of water (CU) to rainfall during the growing season.

The water productivity of rice was determined as the grain yield obtained per unit of rainfall plus irrigation water applied (Chahal et al., 2007).

### 2.3.3 Detection of change in rainfall pattern

As mentioned earlier, 17 locations were selected for the study. To detect the change in rainfall pattern over the study area, the daily rainfall of four stations (located in the study area) based on the availability of data for a period of 1990–2019 was analyzed. These stations are, *viz.*, Pusa (25.98°N, 85.67°E; Samastipur district), Muzaffarpur (26.07°N, 85.24°E; Muzaffarpur district), Motihari (26.65°N, 84.91°E, East Champaran district), and Chhapra (25.78°N, 84.73°E, Saran district). Two sets of data, *viz.*, 1990–2019 and 2010–2019, were considered to detect the changes in mean values of annual rainfall and rainy days, and number of dry days during monsoon. Trends and significance of these parameters were determined based on the Mann-Kendall Test (Mann, 1945; Kendall, 1975; Yadav et al., 2014), which is a function of the ranks of the observations rather than their actual values (Oguntunde et al., 2011). The test is non-parametric for identifying trends and is not affected by the actual distribution of the data and is less sensitive to outliers. Trends of maximum and minimum temperature during different months of the wheat growing season were also worked out.

## 3 Results and discussion

### 3.1 Effect of preponing sowing dates on yield attributes and yield of rice

The grain yield of rice sown during 20–25 May with assured irrigation was found to be 5.2 t $ha^{-1}$, whereas the yield obtained for 10–15 June sown rice with farmers' practice was 3.2 t $ha^{-1}$, which was 62.5% higher over the later sown crop (Table 1). This quantum jump was only because of higher physiological maturity days of the timely sown crop and the availability of proper moisture regimes in the rice field, fed through assured irrigation. In the late-sown crops, the growth period was short that ultimately limited the leaf surface area, panicle length, and number of grains per panicle, probably due to limited moisture in the field during dry spells, as this crop was not scientifically managed by the farmers. Delayed sowing had a bearing on the seed-setting rate. Ahmed et al. (2011) while working on rice observed that the 1,000-grain weight and the seed-setting rate decreased beyond the temperature of 27.0°C. Considering the 1,000-grain weight, it was found to be 6.4% higher in the case of early sown crops (23.0 g) as compared to late-sown crops (21.6 g). Quite contrary to this, the number of unfilled tillers per $m^2$ was found to be 5.8% higher in late-sown crops (24.3), compared to early sown crops (22.9). The critical temperature for inducing spikelet sterility in rice varied from 10 to 15°C (Tinarelli, 1989). Alvarado (2002) found that the average temperature under 20°C for 5 days during flowering stage increased the probability of obtaining spikelet sterility greater than 10–12%. The total biological yield (including both grains and straw) was found to be 52.3% higher in early sown crops (12.18 t $ha^{-1}$) as compared to late-sown crops (8.0 t $ha^{-1}$) with harvest index of 42.8 and 39.8%, respectively. Harvest index refers to quantify the grain yield versus total amount of biological yield that a crop produces, signifying the reproductive efficiency of the crop.

Early sown crops of rice recorded a 19.9% higher number of tillers (245.4 per $m^2$) in comparison with the late-sown crops (204.8 per $m^2$) (Table 2 and Figures 3, 4), which might be ascribed to the fact that younger age (21 days) of the seedlings with higher tillering capacity contributed to this increase. The old aged seedlings, of 30 days or more duration, as in the case of late transplanted rice might have produced a lesser number of tillers, probably some of its early vigor and tiller-bearing capacity got exhausted in the nursery itself because of its age. The aged seedlings as transplanted for late-sown crops might have experienced greater uprooting and transplanting shocks, prompting the crop to remain at an initial slow rate of growth. The number of panicles per $m^2$ and number of grains per panicle in early sown rice were found to be 23.4 and 24.5% higher (222.5 and 142.2, respectively), compared to late transplanted crops (180.5 and 114.3, respectively). The number of empty spikelets increased with shading and low temperature, and a decrease in filled grain percentage was observed due to the lower solar radiation. In long-duration varieties, low light stress synchronizing with the vegetative lag phase resulted in considerable tiller mortality and fewer productive panicles per square meter (Murty et al., 1975). The reasons for higher yield, higher number of tillers per $m^2$, higher number of panicles per $m^2$, and number of grains per panicle might be due to congenial thermal and as well field moisture balance in the timely sown crop than the crops conventionally raised by the farmers. Moisture stress after 10 days of 50% flowering significantly reduced single panicle weight, test weight, fertile spikelets per panicle, and total spikelets per panicle and significantly increased sterile spikelets per panicle.

Weather data presented in Figure 2 revealed that there was hardly any variation in actual and normal rainfall during May. However, June and July experienced deficit rainfall. Under such a water-stressed environment, the resource-poor farmers and the farmers with limited or no provision of irrigation sowed rice during 10–15 June in the nursery and transplanted during 10–15 July in the main field. The

**TABLE 1** Grain yield, total biological yield, and harvest index of rice under timely sown and late-sown conditions.

| Locations | Grain yield (t ha$^{-1}$) | | | Straw yield (t ha$^{-1}$) | | | Biological yield (t ha$^{-1}$) | | | Harvest Index (%) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Timely sown | Late sown | % increase | Timely sown | Late sown | % increase | Timely sown | Late sown | % increase | Timely sown | Late sown | % increase |
| Khodabanpur | 4.99 | 3.05 | 63.6 | 6.49 | 4.62 | 40.5 | 11.49 | 7.67 | 49.7 | 43.5 | 39.8 | 9.3 |
| Jale | 4.77 | 2.91 | 63.9 | 5.72 | 4.41 | 29.7 | 10.49 | 7.32 | 43.3 | 45.5 | 39.7 | 14.4 |
| Piprakothi | 5.22 | 3.2 | 63.3 | 7.31 | 4.83 | 51.3 | 12.53 | 8.03 | 56.1 | 41.7 | 39.8 | 4.6 |
| Parsauni | 4.99 | 3.08 | 62.2 | 7.49 | 4.62 | 62.1 | 12.49 | 7.70 | 62.2 | 42.0 | 40.0 | 0.0 |
| Madhopur | 6.13 | 3.69 | 65.9 | 7.35 | 5.67 | 29.7 | 13.48 | 9.36 | 44.0 | 45.5 | 39.5 | 15.2 |
| Narkatiaganj | 5.45 | 3.31 | 64.4 | 7.08 | 5.04 | 40.5 | 12.53 | 8.35 | 50.0 | 43.5 | 39.7 | 9.6 |
| Manjhi | 5.22 | 3.17 | 64.7 | 6.27 | 4.83 | 29.7 | 11.49 | 8.00 | 43.6 | 45.5 | 39.6 | 14.7 |
| Bhagwanpur Hat | 4.99 | 3.05 | 63.6 | 6.49 | 4.62 | 40.5 | 11.49 | 7.67 | 49.7 | 43.5 | 39.8 | 9.3 |
| Sipaya | 5.45 | 3.34 | 63.1 | 8.17 | 5.04 | 62.1 | 13.62 | 8.38 | 62.5 | 40.0 | 39.9 | 0.4 |
| Sitamarhi | 5.22 | 3.18 | 64.2 | 6.79 | 4.83 | 40.5 | 12.01 | 8.01 | 49.9 | 43.5 | 39.7 | 9.4 |
| Turki | 4.77 | 2.95 | 61.7 | 7.15 | 4.41 | 62.1 | 11.92 | 7.36 | 62.0 | 42.2 | 40.1 | 5.3 |
| Saraiya | 5.22 | 3.2 | 63.3 | 7.31 | 4.83 | 51.3 | 12.53 | 8.03 | 56.1 | 41.7 | 39.8 | 4.6 |
| Sukhet | 4.77 | 2.93 | 62.5 | 6.67 | 4.41 | 51.3 | 11.44 | 7.34 | 55.8 | 41.7 | 40.0 | 4.3 |
| Sheohar | 5.22 | 3.17 | 64.7 | 6.27 | 4.83 | 29.7 | 11.49 | 8.00 | 43.6 | 45.5 | 39.6 | 14.7 |
| Vaishali | 5.45 | 3.3 | 65.2 | 6.54 | 5.04 | 29.7 | 11.99 | 8.34 | 43.7 | 45.5 | 39.6 | 14.9 |
| Birauli | 5.22 | 3.2 | 63.3 | 7.31 | 4.83 | 51.3 | 12.53 | 8.03 | 56.1 | 41.7 | 39.8 | 4.6 |
| Lada | 5.45 | 3.34 | 63.1 | 8.17 | 5.04 | 62.1 | 13.62 | 8.38 | 62.5 | 40.0 | 39.9 | 0.4 |
| Mean | 5.21 | 3.18 | 63.7 | 6.98 | 4.82 | 44.8 | 12.18 | 8.00 | 52.3 | 42.8 | 39.8 | 8.0 |



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TABLE 2 Yield attributes of rice in timely sown and late-sown conditions.

| Locations | Number of tillers (per m$^2$) | | | Number of panicles (per m$^2$) | | | Number of grains per panicle | | | Number of unfilled tillers (per m$^2$) | | | 1,000-grain weight (g) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Timely sown | Late sown | % increase | Timely sown | Late sown | % increase | Timely sown | Late sown | % increase | Timely sown | Late sown | % decrease | Timely sown | Late sown | % increase |
| Khodabanpur | 235.4 | 196.7 | 19.7 | 213.4 | 173.4 | 23.1 | 136.4 | 109.7 | 24.3 | 22.1 | 23.3 | 5.43 | 22.1 | 20.8 | 6.3 |
| Jale | 224.7 | 188.1 | 19.5 | 203.7 | 165.9 | 22.8 | 130.2 | 104.9 | 24.1 | 21.0 | 22.2 | 5.71 | 20.8 | 19.6 | 6.1 |
| Piprakothi | 246.1 | 205.2 | 19.9 | 223.1 | 180.8 | 23.4 | 142.6 | 114.5 | 24.6 | 23.2 | 24.4 | 5.17 | 22.9 | 21.5 | 6.5 |
| Parsauni | 235.4 | 194.8 | 20.9 | 213.4 | 171.3 | 24.6 | 136.4 | 108.7 | 25.5 | 21.9 | 23.5 | 7.31 | 22.3 | 20.8 | 7.2 |
| Madhopur | 288.9 | 245.1 | 17.9 | 261.9 | 216.9 | 20.7 | 167.4 | 136.7 | 22.4 | 27.1 | 28.2 | 4.06 | 26.9 | 25.7 | 4.7 |
| Narkatiaganj | 256.8 | 215.7 | 19.1 | 232.8 | 190.4 | 22.3 | 148.8 | 120.3 | 23.7 | 24.2 | 25.3 | 4.55 | 24.1 | 22.8 | 5.7 |
| Manjhi | 246.1 | 207.1 | 18.8 | 223.1 | 182.9 | 22.0 | 142.6 | 115.5 | 23.4 | 22.9 | 24.2 | 5.68 | 22.9 | 21.7 | 5.5 |
| Bhagwanpur Hat | 235.4 | 196.7 | 19.7 | 213.4 | 173.4 | 23.1 | 136.4 | 109.7 | 24.3 | 21.8 | 23.3 | 6.88 | 21.6 | 20.3 | 6.4 |
| Sipaya | 256.8 | 211.9 | 21.2 | 232.8 | 186.2 | 25.1 | 148.8 | 118.2 | 25.9 | 24.1 | 25.7 | 6.64 | 24.4 | 22.7 | 7.5 |
| Sitamarhi | 246.1 | 206.2 | 19.4 | 223.1 | 181.9 | 22.7 | 142.6 | 115.0 | 24.0 | 22.9 | 24.3 | 6.11 | 22.8 | 21.5 | 6.0 |
| Turki | 224.7 | 185.3 | 21.3 | 203.7 | 162.8 | 25.2 | 130.2 | 103.4 | 26.0 | 21.2 | 22.5 | 6.13 | 21.1 | 19.6 | 7.7 |
| Saraiya | 246.1 | 205.2 | 19.9 | 223.1 | 180.8 | 23.4 | 142.6 | 114.5 | 24.6 | 23.1 | 24.4 | 5.63 | 22.7 | 21.3 | 6.6 |
| Sukhet | 224.7 | 183.4 | 22.6 | 203.7 | 160.7 | 26.8 | 130.2 | 102.3 | 27.3 | 21.7 | 22.7 | 4.61 | 21.5 | 19.8 | 8.6 |
| Sheohar | 246.1 | 207.1 | 18.8 | 223.1 | 182.9 | 22.0 | 142.6 | 115.5 | 23.4 | 22.9 | 24.2 | 5.68 | 23.0 | 21.8 | 5.5 |
| Vaishali | 256.8 | 216.6 | 18.6 | 232.8 | 191.4 | 21.6 | 148.8 | 120.8 | 23.1 | 23.8 | 25.2 | 5.88 | 23.6 | 22.4 | 5.4 |
| Birauli | 246.1 | 203.3 | 21.1 | 223.1 | 178.7 | 24.8 | 142.6 | 113.4 | 25.7 | 22.8 | 24.6 | 7.89 | 23.1 | 21.5 | 7.4 |
| Lada | 256.8 | 213.8 | 20.1 | 232.8 | 188.3 | 23.7 | 148.8 | 119.3 | 24.8 | 23.9 | 25.5 | 6.69 | 25.5 | 24.0 | 6.3 |
| Mean | 245.5 | 204.8 | 19.9 | 222.5 | 180.5 | 23.4 | 142.2 | 114.3 | 24.5 | 23.0 | 24.3 | 5.89 | 23.0 | 21.6 | 6.4 |



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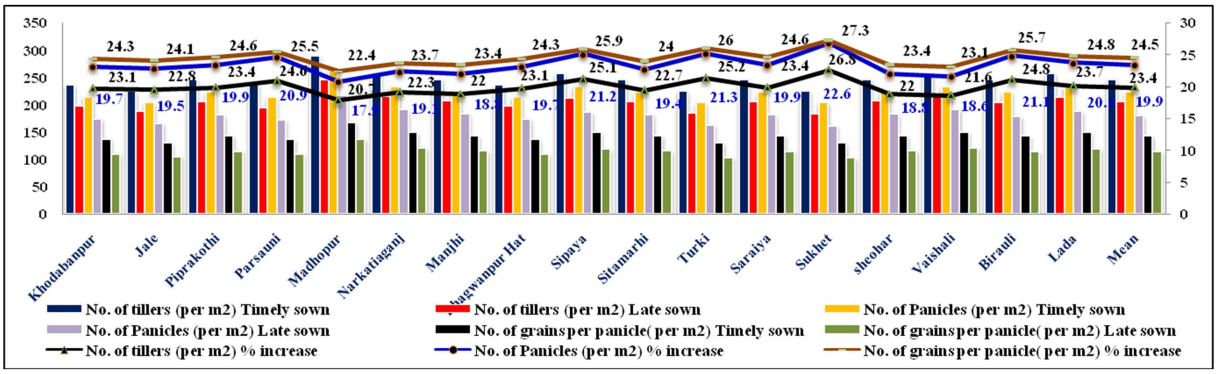


FIGURE 3
Yield attributing traits such as number of tillers per m$^2$, number of panicles per m$^2$, and number of grains per panicle under timely and late-sown rice in Bihar.

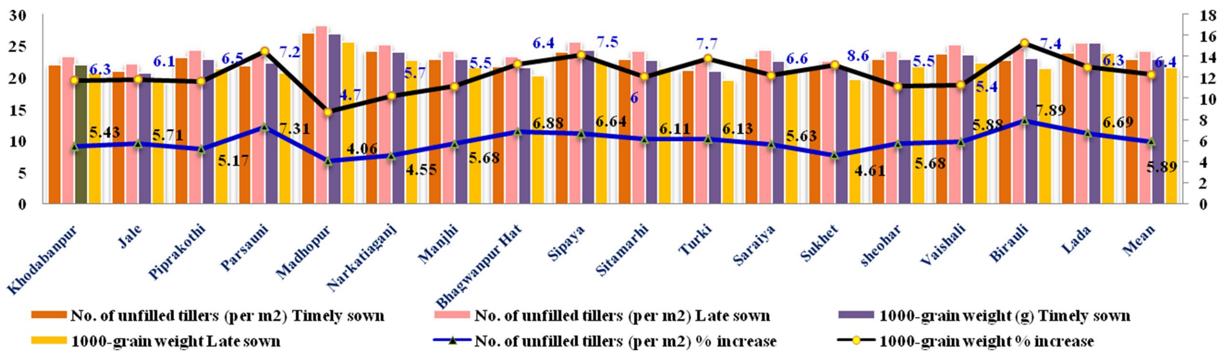


FIGURE 4
Yield attributing traits such as number of unfilled tillers per m$^2$ and 1,000 grain weight under timely sown and late-sown rice in Bihar.

experiment revealed that in the late transplanted rice as in the case of farmers' practice, the days taken to attain 50% flowering decreased substantially as compared to early sown crops. The 15–20 June transplanted rice took 91 days to attain 50% flowering and 116 days to attain the dough stage, while the 10–15 July transplanted rice took 84 days to attain 50% flowering and 101 days to attain the dough stages. Thermal time exerts great influence on the growth and yield of crops. Sattar et al. (2017) observed that the rice crop sown on 15 July required 2 days more to attain the maximum tillering stage than that sown on 31 May. However, the duration required to attain 50% flowering on 31 May and 15 July sown crops was 109 and 96 days, respectively. The crop sown on 31 May attained maturity in 142 days, while the crop sown on 31 July reached maturity in 119 days. Kobayashi et al. (2010) concluded that higher air temperature and incident radiation tend to advance anthesis in rice. Thus, delayed transplanting forced the crop to pass through a relatively lower temperature regime during its reproductive phase (Bal et al., 2023). They also reported significant variation in rice yield in response to weather variabilities during different growth phases of the crop under the diverse ecosystems of India. Srivastava et al. (2018) observed that with delayed transplanting, the percentage of chaffy grains per panicle increased, which resulted in reduced grain yields. This is in conformity with the results of previous research, where the setting of lower temperature resulted in the irregular opening of flowers and inadequate filling of the panicles (Venkataraman and Krishnan, 1992). The maximum temperature required for proper germination of pollen should be 33–34°C (Grist, 1986). Moreover, late transplanting produced lower yields due to the higher percentage of chaffy grains in the panicle under a non-congenial temperature regime (Anon, 2016). The formation of chaffy grains coincided with the prevalence of lower air temperature ($T_{max} < 32.5°C$ and $T_{min} < 23.0°C$) during the 50% flowering to dough stage of rice crop (Sattar et al., 2017).

## 3.2 Effect of preponing sowing dates of rice on yield and productivity of succeeding wheat crop

In the rice–wheat–green gram cropping system, the HD-2967 variety of wheat was sown on 7 November after the harvest of paddy on 30 October under a timely sown assured irrigation system, whereas in the farmers' practice, wheat was sown during 25–30 November after the harvest of paddy crops during 15–20 November. Timely sowing of wheat in the cropping system in the experimental plots was made possible because of the timely harvesting of the previous rice crop. This resulted in a drastic change in yield and yield attributing characteristics of wheat. On average, a 61% increase in grain yield was observed for the crop sown at the appropriate sowing window, compared to late sowing (Table 3). In one study at New Delhi, a decrease in wheat yield by 70, 29, and 77 kg ha$^{-1}$ per day due to delay in sowing beyond the first week of November was observed in varieties HD-2932, WR-544, and HD-2967, respectively (Dubey et al., 2019). In our study, the total biological yield (both grain and straw) was 51.3% higher in timely sown wheat (11.8 t ha$^{-1}$), as compared to late-sown wheat (7.8 t ha$^{-1}$) with a 6.6% increase in harvest index. The lower grain, straw, and biological yields in the late-sown wheat might be due to the negative impact of higher temperature regimes and terminal heat stress during its flowering and milking stages (Sattar et al., 2020; Sattar and Srivastava, 2021). They reported enhanced productivity of rice–wheat cropping system in Indo-Gangetic plains through manipulation of sowing windows of both crops. The number of shoots per m$^2$, number of spikes per m$^2$, and number of grains per spike in the timely sown wheat were 9.0, 9.0, and 24.8% higher, respectively, as compared to late-sown wheat (Table 4 and Figure 5). The number of fertile spikelets and 1,000-grain weight were also found to be, respectively, 8.9 and 6.3% higher in timely sown wheat as compared to late-sown wheat, whereas the number of unfilled spikes was 9.4% higher in late-sown wheat as compared to timely sown wheat (Figure 6). In case of grain yield, it was observed to be 60.9% higher in timely sown wheat (4.9 t ha$^{-1}$) as compared to late-sown wheat (3.05 t ha$^{-1}$). Both maximum temperature and minimum temperature played a decisive role in determining the grain yield of wheat. Optimum thresholds of maximum and minimum temperatures during different growth stages of wheat for achieving higher yields in the study area revealed that temperature above 30.2°C during the 50% flowering to the milking stage and temperature above 33.1°C during the 50% flowering to maturity stage reduced grain yield below 2.0 t ha$^{-1}$. Similarly, a minimum temperature of 16.8°C during the 50% flowering to the milking stage and a minimum temperature of 18°C during the 50% flowering to maturity stage significantly affected the crop yield, and it produced a yield below 2.0 t ha$^{-1}$. For achieving a yield target of 4.0 t ha$^{-1}$ or more, Sattar et al. (2020) while working on crop weather relationships on wheat observed that the maximum and minimum temperatures from sowing to tiller formation should be 23.7 and 11.8°C, respectively. Similarly, the maximum and minimum temperatures from 50% flowering to milking should be 24.6 and 11.6°C, respectively, and from 50% flowering to maturity, it should be 29.2 and 14.4°C, respectively (Table 5).

A comparative analysis of the ideal temperature (Table 5) suitable for wheat growth and actual temperature during the experimental years (Table 6) revealed that the wheat crop sown on 7 November experienced optimum temperature during flowering to maturity stages, while the late-sown crop encountered higher temperature, resulting in lesser number of panicles per m$^2$, lesser number of grains per panicle, lesser 1,000-grain weight, and higher number of unfilled grains per m$^2$. Moreover, there is a general trend of increasing minimum temperature and decreasing maximum temperature during the later growing period of wheat (Table 7), which tends to increase the rate of photorespiration and thereby reduces the net photosynthesis. Accordingly, the increase in minimum temperature in general tends to affect the process of anthesis to a great extent. It could be inferred from the results that the sowing of wheat around 7 November instead of 25–30 November could reduce the negative impact of increasing temperature during the fag end of the growing season on the growth and yield of wheat and consequently help the farmers to achieve higher yield.

### 3.3 Changing rainfall patterns in the study area, crop water productivity, and effective rainfall for timely and late transplanted rice

Since we are discussing about the importance of monsoon rainfall, climatic risks and assured rainfall on rice productivity, and its sustainability under timely and late conditions, it would be prudent to assess the trend and variability of rainfall in the study area in relation to the water use and water productivity of rice. In this context, we have evaluated the change in rainfall patterns using time series data. The result revealed that rainfall in the study area has decreased significantly, leading to drier conditions in the recent 10-year period (Table 8). The maximum number of dry days during the monsoon season over the last 30 years (1990–2019) was observed to be 70 days, which increased to 87 days during the recent 10-year period (2010–2019). The peak rate of increase in the number of dry days during monsoon is calculated as 1.5 days per year, signifying the decrease in annual rainy days in the region. Moreover, decreasing trends in annual rainfall were found to occur over the area. This poses a threat to the sustainability of rice crop production as more than 60% of rice is cultivated under rainfed conditions during monsoon season. Hence, erratic behavior of rainfall, decreasing number of rainy days, and increasing dry spell have enormous stakes in rice productivity. In this context, it is necessary to adopt climate-resilient interventions such as changing planting schedule, community irrigation approach, and provision of assured irrigation to sustain rice production in the region. A dry spell if coincided with critical growth stages of rice leads to reduced crop yield and sometimes crop failure. Sattar and Srivastava (2021) evaluated the performance of rice crops under different moisture regimes as induced by different planting dates and observed that shifting planting dates helped achieve higher water productivity and grain yield.

The data on water productivity and effective rainfall of timely and late transplanted rice grown at 17 locations of the study area revealed that the water productivity of timely transplanted *kharif* rice ranged from 0.673 kg m$^{-3}$ ha$^{-1}$ at Khodabanpur to 1.052 kg m$^{-3}$ ha$^{-1}$ at Madhopur (Table 9 and Figure 7). On the other hand, it varied from 0.370 kg m$^{-3}$ ha$^{-1}$ at Bhagwanpur Hat to 0.560 kg m$^{-3}$ ha$^{-1}$ at Madhopur for late transplanted rice. The highest water productivity of rice for both timely and late transplanted conditions was recorded for Madhopur, while lower values were observed for Khodabanpur. It was observed that the average water productivity of timely transplanted rice was 85.8% higher than that of late transplanted one. Studies showed that the water productivity of rice can be increased by shifting transplanting dates (Jalota et al., 2009; Sattar and Srivastava, 2021). The higher water productivity of timely transplanted rice in comparison with late transplanted one may be attributed to higher yield, resulting from longer growing period and assured irrigation. The water productivity decreased with a decrease in crop duration when transplanting was delayed beyond 30 June (Sattar and Srivastava, 2021). While considering the irrigation water productivity for timely and late transplanted rice, it was found to vary from a low of 2.38 kg m$^{-3}$ ha$^{-1}$ to a high of 8.76 kg m$^{-3}$ ha$^{-1}$ and from 1.45 to 5.27 kg m$^{-3}$ ha$^{-1}$, respectively (Figure 8). The highest and the lowest values of irrigation water productivity under both conditions were associated with rice grown at Bhagwanpur Hat and Madhopur, respectively. The water productivity of rice in the present study under timely and late

TABLE 3 Yield and yield attributes of wheat under timely sown and late-sown conditions.

| Locations | Number of fertile spikelets/ spike | | | Grain yield (t ha$^{-1}$) | | | Straw yield (t ha$^{-1}$) | | | Biological yield (t ha$^{-1}$) | | | Harvest index (%) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Timely sown | Late sown | % increase | Timely sown | Late sown | % increase | Timely sown | Late sown | % increase | Timely sown | Late sown | % increase | Timely sown | Late sown | % increase |
| Khodabanpur | 18.3 | 16.4 | 11.6 | 4.69 | 2.94 | 59.5 | 6.38 | 4.5 | 41.6 | 11.07 | 7.45 | 48.7 | 42.4 | 39.5 | 7.3 |
| Jale | 17.2 | 15.3 | 12.4 | 4.47 | 2.8 | 59.6 | 5.61 | 4.29 | 30.6 | 10.07 | 7.09 | 42.1 | 44.3 | 39.5 | 12.4 |
| Piprakothi | 19.4 | 17.5 | 10.9 | 4.92 | 3.09 | 59.4 | 7.20 | 4.71 | 52.7 | 12.12 | 7.80 | 55.4 | 40.6 | 39.6 | 2.6 |
| Parsauni | 18.5 | 16.2 | 14.2 | 4.69 | 2.97 | 58.1 | 7.38 | 4.82 | 53.0 | 12.07 | 7.79 | 55.0 | 38.9 | 38.1 | 2.0 |
| Madhopur | 23.2 | 21.4 | 8.4 | 5.83 | 3.58 | 62.6 | 7.24 | 5.55 | 30.4 | 13.07 | 9.14 | 43.0 | 44.6 | 39.2 | 13.7 |
| Narkatiaganj | 20.3 | 18.5 | 9.7 | 5.15 | 3.2 | 60.7 | 6.97 | 4.92 | 41.5 | 12.12 | 8.13 | 49.1 | 42.5 | 39.4 | 7.8 |
| Manjhi | 19.2 | 17.2 | 11.6 | 4.92 | 3.06 | 60.8 | 6.15 | 4.71 | 30.5 | 11.07 | 7.77 | 42.4 | 44.4 | 39.4 | 12.9 |
| Bhagwanpur Hat | 18.3 | 16.1 | 13.7 | 4.69 | 2.94 | 59.5 | 6.38 | 4.50 | 41.6 | 11.07 | 7.45 | 48.7 | 42.4 | 39.5 | 7.3 |
| Sipaya | 20.7 | 18.4 | 12.5 | 5.15 | 3.03 | 69.8 | 8.06 | 4.92 | 63.7 | 13.21 | 7.95 | 66.0 | 39.0 | 38.1 | 2.3 |
| Sitamarhi | 19.3 | 17.2 | 12.2 | 4.92 | 3.07 | 60.1 | 6.67 | 4.71 | 41.6 | 11.59 | 7.79 | 48.9 | 42.4 | 39.5 | 7.5 |
| Turki | 17.5 | 15.5 | 12.9 | 4.47 | 2.84 | 57.4 | 7.04 | 4.53 | 55.3 | 11.50 | 7.37 | 56.1 | 38.8 | 38.5 | 0.8 |
| Saraiya | 19.4 | 17.4 | 11.5 | 4.92 | 3.09 | 59.4 | 7.20 | 4.71 | 52.7 | 12.12 | 7.80 | 55.4 | 40.6 | 39.6 | 2.6 |
| Sukhet | 17.7 | 16.0 | 10.6 | 4.47 | 2.82 | 58.2 | 6.56 | 4.29 | 52.8 | 11.03 | 7.12 | 54.9 | 40.5 | 39.7 | 2.1 |
| Sheohar | 19.2 | 17.2 | 11.6 | 4.92 | 3.06 | 60.8 | 6.15 | 4.71 | 30.5 | 11.07 | 7.77 | 42.4 | 44.4 | 39.4 | 12.9 |
| Vaishali | 20.2 | 18.1 | 11.6 | 5.15 | 3.19 | 61.3 | 6.42 | 4.92 | 30.5 | 11.57 | 8.11 | 42.6 | 44.5 | 39.3 | 13.1 |
| Birauli | 19.6 | 17.1 | 14.6 | 4.92 | 3.09 | 59.4 | 7.20 | 4.71 | 52.7 | 12.12 | 7.80 | 55.4 | 40.6 | 39.6 | 2.6 |
| Lada | 20.5 | 18.2 | 12.6 | 5.1 | 3.01 | 69.4 | 8.06 | 4.95 | 62.8 | 13.16 | 7.96 | 65.3 | 38.8 | 37.8 | 2.5 |
| Mean | 19.3 | 17.3 | 11.9 | 4.90 | 3.05 | 61.0 | 6.86 | 4.73 | 45.0 | 11.77 | 7.78 | 51.3 | 41.8 | 39.2 | 6.6 |

TABLE 4 Yield attributes of wheat under timely sown and late-sown conditions.

| Locations | Number of shoots (per $m^2$) | | | Number of spikes (per $m^2$) | | | Number of unfilled spikes (per $m^2$) | | | Number of grains per spike | | | 1,000-grain weight (g) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Timely sown | Late sown | % increase | Timely sown | Late sown | % increase | Timely sown | Late sown | % decrease | Timely sown | Late sown | % increase | Timely sown | Late sown | % increase |
| Khodabanpur | 429.6 | 395.0 | 8.8 | 320.1 | 294.7 | 8.6 | 100.3 | 109.5 | 9.2 | 52.5 | 40.6 | 29.1 | 32.1 | 30.5 | 5.2 |
| Jale | 414.6 | 382.2 | 8.5 | 305.6 | 282.0 | 8.3 | 100.1 | 109.0 | 8.9 | 48.2 | 38.9 | 24.1 | 30.8 | 29.3 | 5.1 |
| Piprakothi | 444.5 | 407.8 | 9.0 | 334.7 | 307.4 | 8.9 | 100.4 | 109.9 | 9.4 | 52.8 | 42.4 | 24.6 | 32.9 | 31.2 | 5.4 |
| Parsauni | 429.6 | 392.1 | 9.5 | 320.1 | 291.1 | 10.0 | 101.0 | 109.5 | 8.4 | 50.5 | 40.2 | 25.5 | 32.3 | 30.5 | 5.9 |
| Madhopur | 504.5 | 467.7 | 7.9 | 392.9 | 368.7 | 6.5 | 98.9 | 111.6 | 12.8 | 62.0 | 50.6 | 22.4 | 31.9 | 29.3 | 8.8 |
| Narkatiaganj | 459.5 | 423.5 | 8.5 | 349.2 | 323.6 | 7.9 | 99.9 | 110.3 | 10.5 | 55.1 | 44.6 | 23.7 | 32.3 | 30.1 | 7.3 |
| Manjhi | 444.5 | 410.7 | 8.3 | 334.7 | 310.9 | 7.6 | 99.7 | 109.9 | 10.2 | 52.8 | 42.8 | 23.4 | 32.9 | 31.4 | 4.7 |
| Bhagwanpur Hat | 429.6 | 395.0 | 8.8 | 320.1 | 294.7 | 8.6 | 100.3 | 109.5 | 9.2 | 50.5 | 40.6 | 24.3 | 31.6 | 30.0 | 5.3 |
| Sipaya | 459.5 | 417.8 | 10.0 | 349.2 | 316.5 | 10.3 | 101.3 | 110.3 | 8.9 | 55.1 | 43.8 | 25.9 | 32.1 | 29.3 | 9.5 |
| Sitamarhi | 444.5 | 409.2 | 8.6 | 334.7 | 309.1 | 8.3 | 100.1 | 109.9 | 9.8 | 52.8 | 42.6 | 24.0 | 32.8 | 31.2 | 5.1 |
| Turki | 414.6 | 377.9 | 9.7 | 305.6 | 276.7 | 10.4 | 101.2 | 109.0 | 7.7 | 48.2 | 38.3 | 26.0 | 31.1 | 29.3 | 6.1 |
| Saraiya | 444.5 | 407.8 | 9.0 | 334.7 | 307.4 | 8.9 | 100.4 | 109.9 | 9.4 | 52.8 | 42.4 | 24.6 | 32.7 | 31.0 | 5.4 |
| Sukhet | 414.6 | 375.0 | 10.5 | 305.6 | 273.1 | 11.9 | 101.9 | 109.0 | 7.0 | 48.2 | 37.9 | 27.3 | 31.5 | 29.5 | 6.7 |
| Sheohar | 444.5 | 410.7 | 8.3 | 334.7 | 310.9 | 7.6 | 99.7 | 109.9 | 10.2 | 52.8 | 42.8 | 23.4 | 33.0 | 31.5 | 4.7 |
| Vaishali | 459.5 | 424.9 | 8.1 | 349.2 | 325.4 | 7.3 | 99.5 | 110.3 | 10.9 | 55.1 | 44.8 | 23.1 | 33.6 | 32.1 | 4.6 |
| Birauli | 444.5 | 405.0 | 9.8 | 334.7 | 303.8 | 10.2 | 101.2 | 109.9 | 8.6 | 52.8 | 42.0 | 25.7 | 33.1 | 31.2 | 6.0 |
| Lada | 459.5 | 420.6 | 9.2 | 349.2 | 320.0 | 9.1 | 100.6 | 110.3 | 9.7 | 55.1 | 44.2 | 24.8 | 31.0 | 27.9 | 11.1 |
| Mean | 443.7 | 407.2 | 9.0 | 333.8 | 306.8 | 8.9 | 100.4 | 109.9 | 9.4 | 52.8 | 42.3 | 24.8 | 32.2 | 30.3 | 6.3 |


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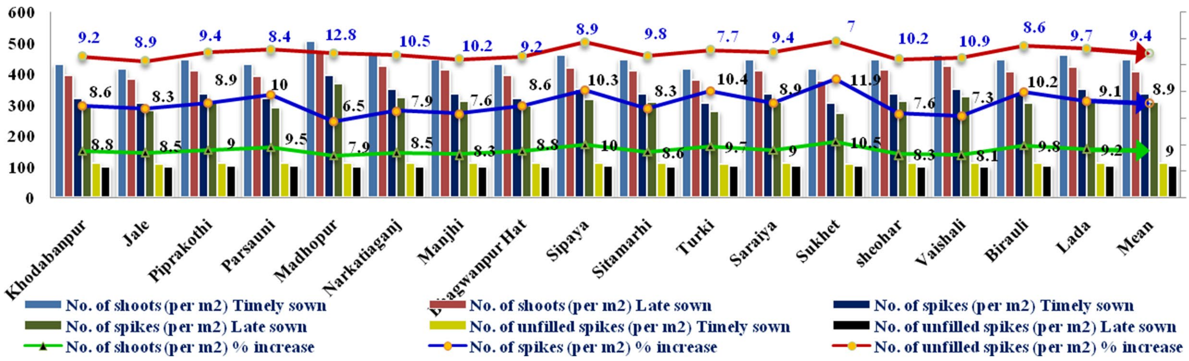


FIGURE 5
Yield attributing traits such as number of shoots per $m^2$, number of spike per $m^2$, and number of unfilled spike per $m^2$ under timely sown and late-sown wheat crops.

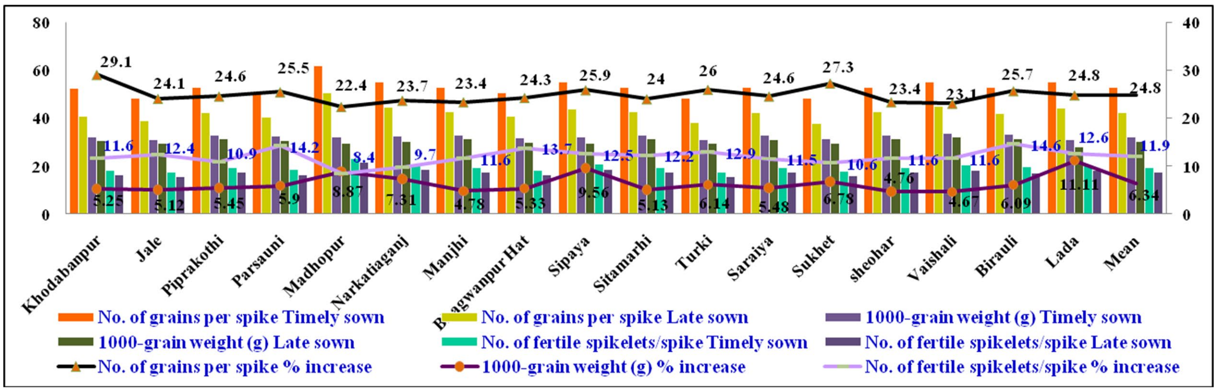


FIGURE 6
Yield attributing traits such as number of grains per spike, 1,000 grain weight, number of fertile spikes, and number of grains per spike under timely sown and late-sown wheat crops.

**TABLE 5** Thresholds of optimum temperature for wheat yield in the study area.

| Sowing to tiller initiation | | 50% flowering to milking | | 50% flowering to maturity | | Yield levels (t $ha^{-1}$) |
|---|---|---|---|---|---|---|
| $T_{max}$ (°C) | $T_{min}$ (°C) | $T_{max}$ (°C) | $T_{min}$ (°C) | $T_{max}$ (°C) | $T_{min}$ (°C) | |
| 22.6 | 7.6 | 30.2 | 16.8 | 33.1 | 18.0 | < 2.0 |
| 24.0 | 9.2 | 29.4 | 15.1 | 32.1 | 17.2 | > 2.0 and < 3.0 |
| 22.5 | 9.8 | 26.9 | 13.1 | 30.4 | 15.7 | > 3.0 and < 4.0 |
| 23.7 | 11.8 | 24.6 | 11.6 | 29.2 | 14.4 | > 4.0 |

$T_{max}$, maximum temperature; $T_{min}$, minimum temperature.

conditions varies with other studies conducted elsewhere, perhaps due to differential growing environments, growing period length, water use, and grain yield. While working on rice water productivity, Tuong et al. (2005) reported an average water productivity of 0.4 kg grain $m^{-3}$ with respect to total water input (irrigation plus rainfall). Under water-stressed environment, an increase in water productivity to 0.8–1.0 kg grain $m^{-3}$ was reported (Kato et al., 2009; de Vries et al., 2010). Zwart and Bastiaanssen (2004) estimated the water productivity and evapotranspiration requirement of rice as 0.6–1.6 kg $m^{-3}$ and 400–800 mm, respectively.

The variations in effective rainfall during the growing season of early and late transplanted rice are presented in Table 9. In general, the effective rainfall was higher for the late transplanted rice. The effective rainfall for timely transplanted rice ranged from a low of 553.0 mm to a high of 741.3 mm across the study area. In the case of late transplanted rice, it was found to vary from 658.8 to 825.3 mm. Since the late transplanted crop in farmers' field faced moisture stress of varying intensity, the efficiency of rainwater utilization was much higher leading to higher effective rainfall. A small amount of rainfall in dry soils could be more useful and effective, whereas the same

TABLE 6 Average thermal time and maximum temperature during different phenological stages of wheat.

| Date of sowing | 50% flowering stage | | Milk stage | | Dough stage | | Physiological maturity | |
|---|---|---|---|---|---|---|---|---|
| | Thermal time | Temp (°C) | Thermal time | Temp (°C) | Thermal time | Temp (°C) | Thermal time | Temp (°C) |
| 7 Nov | 5 Feb | 25.0 | 16 Feb | 25.8 | 15 Mar | 29.8 | 7 Apr | 34.6 |
| 25 Nov | 14 Feb | 26.8 | 23 Feb | 27.8 | 25 Mar | 34.03 | 20 Apr | 37.0 |

TABLE 7 Temperature trends during the wheat growing season at Pusa located in the study area (database 1990–2019).

| Parameters | November | December | January | February | March | Annual |
|---|---|---|---|---|---|---|
| $T_{max}$ (°C) | *(D) | **(D) | **(D) | NS(D) | *(D) | **(D) |
| $T_{min}$ (°C) | *(I) | **(I) | **(I) | **(I) | *(I) | **(I)` |

D, decreasing trend; I, increasing trend; NS, non-significant; $T_{max}$, maximum temperature; $T_{min}$, minimum temperature. *$p$ = 0.05, **$p$ = 0.01.

TABLE 8 Trend statistics of annual rainfall, number of dry days during monsoon, and annual rainy days at different locations over the study area.

| Stations | Parameters | Annual rainfall (mm) | No. of dry days during monsoon | No. of annual rainy days |
|---|---|---|---|---|
| Pusa | Average (30 years, 1990–2019) | 1258.9 | 66.0 | 58.0 |
| | Preceding 10-year average (2010–2019) | 1012.8 | 73.0 | 49.0 |
| | Trends over 30 years (1990–2019) | −9.6 | +0.543* | −0.380 |
| Muzaffarpur | Average (30 years, 1990–2019) | 1222.8 | 67.0 | 56.0 |
| | Preceding 10-year average (2010–2019) | 850.6 | 71.0 | 46.0 |
| | Trends over 30 years (1990–2019) | −18.9* | +0.289 | −0.557* |
| Chhapra | Average (30 years, 1990–2019) | 1151.2 | 70.0 | 54.0 |
| | Preceding 10-year average (2010–2019) | 817.3 | 87.0 | 39.0 |
| | Trends over 30 years (1990–2019) | −21.8** | +1.456** | −0.988** |
| Motihari | Average (30 years, 1990–2019) | 1406.2 | 68.0 | 59.0 |
| | Preceding 10-year average (2010–2019) | 1294.8 | 70.0 | 58.0 |
| | Trends over 30 years (1990–2019) | 3.6 | +0.224 | −0.099 |

*$p$ = 0.05, **$p$ = 0.01.

amount of rainfall in wet soil may be insignificant. Chang (1963) observed that the effective rainfall increased with the storage capacity and drying condition of the soil. In the present study, lesser rainfall availed for late transplanted crops might have been more effective in meeting evapotranspiration requirements of the crop. On the other hand, for early transplanted crops, a higher fraction might have been ineffective due to seepage and percolation losses.

Considering water-saving methods, direct seeded rice (DSR) and System of Rice Intensification (SRI) planting methods of rice are gaining importance under water-stressed environments in the wake of climate change. At present, it is only about 2.5% of the total rice-growing area in Bihar. In the study area, the farmers tend to opt it for upland areas under conditions of erratic monsoon. On the other hand, the SRI method does not find any taker among the farmers of the region.

## 3.4 Effect of early wheat harvesting on the yield of subsequent green gram

The manipulation of sowing dates of both rice and wheat in the cropping system provided sufficient space and opportunity for the sowing of green gram at appropriate time with the provision of assured irrigation. Thus, the early sowing of rice–wheat helped us to achieve a grain yield of green gram to the tune of 7.21 t ha$^{-1}$ (Table 10), whereas in the farmers' practice, the yield was much lower (6.09 t ha$^{-1}$). An obvious increase of 18.4% in the grain yield of green gram was recorded.

## 3.5 Effect of optimization of the sowing window on the system productivity and economics of rice–wheat–green gram system

The cropping intensity of experimental plots and the farmers' practice was found to be >300%. However, the rice equivalent yield (REY) of timely sown assured irrigation plots was found to be 13.25 t ha$^{-1}$, whereas under farmers' practice (delayed condition), REY was observed as 8.89 t ha$^{-1}$. The production efficiency was found to be 35.3 kg ha$^{-1}$ day$^{-1}$ for timely sown assured irrigation plots. On the other hand, it was paltry (24.0 kg ha$^{-1}$ day$^{-1}$) under farmers' practice. In the case of the land use efficiency, it was found

TABLE 9 Yield, water productivity, and effective rainfall for timely and late transplanted *kharif* rice at different locations over the study area.

| Location | Yield, water productivity, and effective rainfall for timely transplanted rice | | | | Yield, water productivity, and effective rainfall for late transplanted rice | | | |
|---|---|---|---|---|---|---|---|---|
| | Yield (kg ha$^{-1}$) | Water requirement (mm) | Water productivity (kg m$^{-3}$ ha$^{-1}$) | Effective rainfall (mm) | Yield (kg ha$^{-1}$) | Water requirement (mm) | Water productivity (kg m$^{-3}$ ha$^{-1}$) | Effective rainfall (mm) |
| Khodabanpur | 4,990 | 531.3 | 0.673 | 741.3 | 3,054 | 585.4 | 0.384 | 795.4 |
| Jale | 4,770 | 524.4 | 0.802 | 594.4 | 2,911 | 615.4 | 0.425 | 685.4 |
| Piprakothi | 5,220 | 522.8 | 0.788 | 662.7 | 3,220 | 606.6 | 0.431 | 746.6 |
| Parsauni | 4,991 | 517.7 | 0.759 | 657.7 | 3,087 | 606.6 | 0.413 | 746.6 |
| Madhopur | 6,132 | 512.9 | 1.052 | 582.9 | 3,692 | 588.8 | 0.560 | 658.8 |
| Narkatiaganj | 5,452 | 483.0 | 0.986 | 553.0 | 3,310 | 592.3 | 0.500 | 662.3 |
| Manjhi | 5,220 | 529.2 | 0.706 | 739.2 | 3,176 | 615.3 | 0.385 | 825.3 |
| Bhagwanpur Hat | 4,991 | 527.9 | 0.676 | 737.8 | 3,054 | 615.3 | 0.370 | 825.3 |
| Sipaya | 5,451 | 519.8 | 0.747 | 729.8 | 3,346 | 600.3 | 0.413 | 810.3 |
| Sitamarhi | 5,223 | 518.7 | 0.793 | 658.6 | 3,182 | 606.1 | 0.426 | 746.1 |
| Turki | 4,770 | 525.6 | 0.717 | 665.5 | 2,958 | 614.1 | 0.392 | 754.1 |
| Saraiya | 5,221 | 511.8 | 0.801 | 651.7 | 3,201 | 614.1 | 0.424 | 754.1 |
| Sukhet | 4,757 | 516.4 | 0.725 | 656.3 | 2,932 | 603.8 | 0.394 | 743.8 |
| Sheohar | 5,224 | 517.5 | 0.718 | 727.5 | 3,175 | 606.1 | 0.389 | 816.1 |
| Vaishali | 5,450 | 526.7 | 0.817 | 666.7 | 3,300 | 614.7 | 0.437 | 754.7 |
| Birauli | 5,227 | 524.4 | 0.787 | 664.4 | 3,200 | 615.7 | 0.423 | 755.7 |
| Lada | 5,452 | 523.3 | 0.822 | 663.2 | 3,340 | 618.7 | 0.440 | 758.7 |
| Mean | – | – | 0.786 | – | – | – | 0.423 | – |

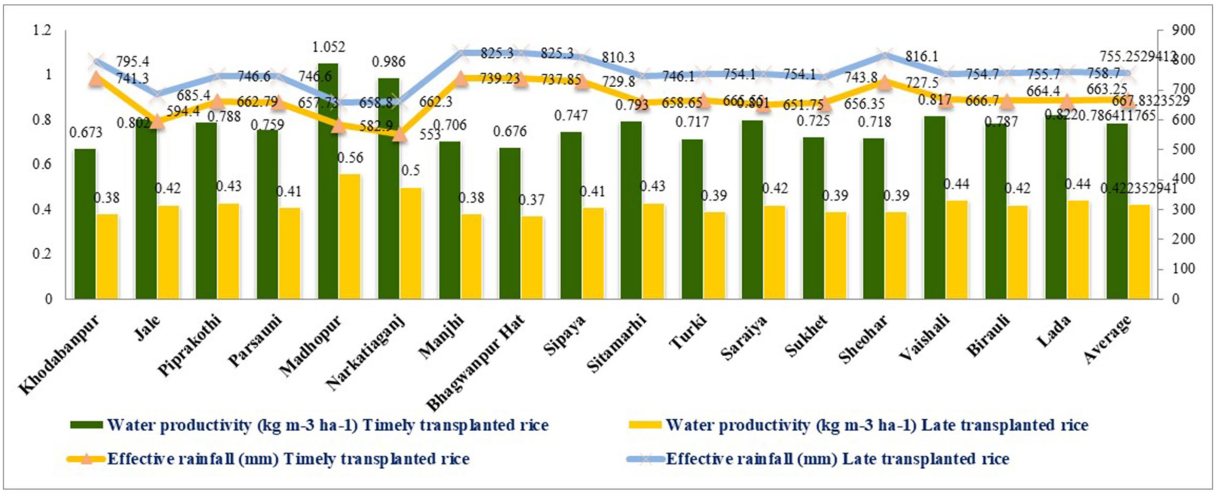


FIGURE 7
Water productivity and effective rainfall for timely and late transplanted *kharif* rice at different locations over the study area.

to be 96.9% under timely sown assured irrigation plots, and under farmers' practice, it was 93.1%. Net return from rice was found to be INR 76117.00 per hectare with a benefit: cost ratio of 2.15 in the timely sown crop as against the net return of INR 36803.00 with benefit: cost ratio of 1.04 under the farmers' practice. Considering wheat from the same piece of land, the net return was INR 86890.00 with benefit: cost ratio of 2.44 in the treated plots as against INR 59315.00 and 1.72, respectively, from the farmers' practice. The green gram provided a net return of INR 34972.00 with benefit: cost ratio of 1.54 in the treated plots as against the net return of INR 25160.00 with benefit: cost ratio of 1.05 for the crop grown under farmers' practice.

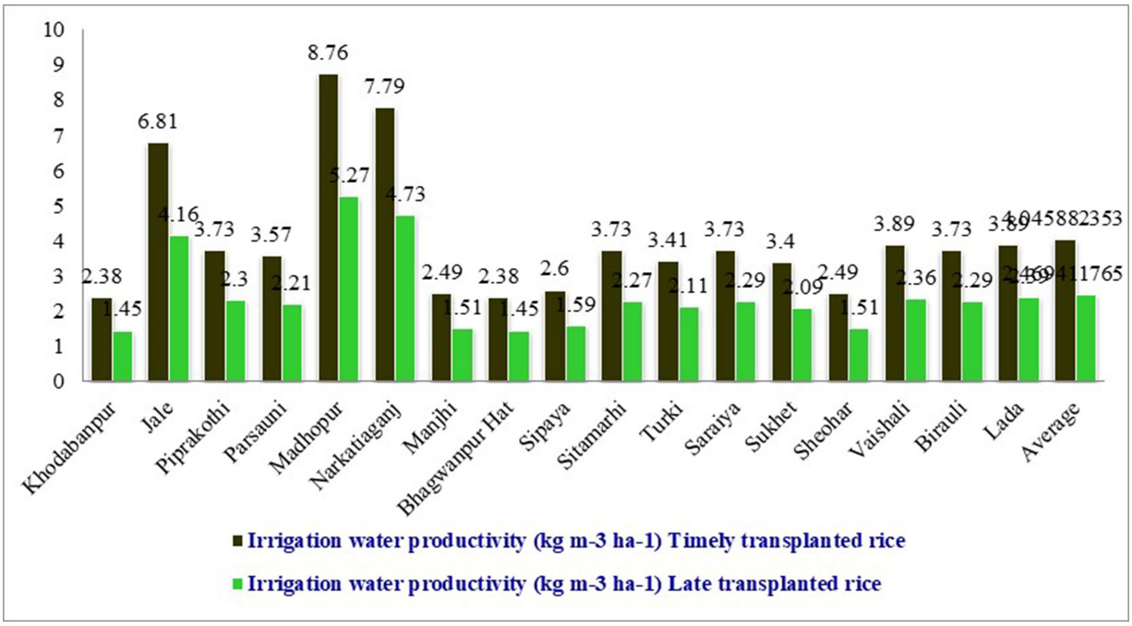


FIGURE 8
Irrigation water productivity of timely and late transplanted *kharif* rice at different locations over the study area.

**TABLE 10 Yield performance of green gram at different locations under timely sown and late-sown conditions.**

| Locations | Grain yield (t ha$^{-1}$) | | |
|---|---|---|---|
| | Timely sown | Late sown | % increase |
| Khodabanpur | 6.90 | 5.88 | 17.3 |
| Jale | 6.57 | 5.60 | 17.3 |
| Piprakothi | 7.24 | 6.17 | 17.3 |
| Parsauni | 6.90 | 5.94 | 16.2 |
| Madhopur | 8.57 | 7.17 | 19.5 |
| Narkatiaganj | 7.57 | 6.41 | 18.1 |
| Manjhi | 7.24 | 6.12 | 18.2 |
| Bhagwanpur Hat | 6.90 | 5.88 | 17.3 |
| Sipaya | 7.57 | 6.06 | 24.9 |
| Sitamarhi | 7.24 | 6.15 | 17.7 |
| Turki | 6.57 | 5.68 | 15.7 |
| Saraiya | 7.24 | 6.17 | 17.3 |
| Sukhet | 6.57 | 5.65 | 16.3 |
| Sheohar | 7.24 | 6.12 | 18.3 |
| Vaishali | 7.57 | 6.38 | 18.7 |
| Birauli | 7.24 | 6.17 | 17.3 |
| Lada | 7.50 | 6.02 | 24.6 |
| Mean | 7.21 | 6.09 | 18.4 |

## 4 Conclusion

By manipulating the sowing dates of rice and wheat, the adverse impacts of climate variability can be minimized to achieve higher system productivity. Moreover, the provision of an assured irrigation system can help ward off the negative impact of dry spells and unfavorable soil moisture regimes on rice production. The major source of irrigation is groundwater, which is extracted by diesel pump sets or by a three-phase 5/7.5 hp. electric pumping system. However, this requires high infrastructure, which is time taking, and voltage fluctuation is a major limiting factor. The high cost of irrigation coupled with the late onset of monsoon is also a major factor, which compels the farmers of the region to go for late sowing and late transplanting. Hence, the productivity of the crop remains low, and under such situation, the state is bound to grow rice in 3.2 million hectares to meet the food requirements. If infrastructure is created for less costly irrigation systems with 3-hp single-phase tube wells fitted with submersible pumps, the productivity can be increased by 50–60% and the food demand of the state can be supported with only 1.2–1.5 million hectares of land with a lower cost of cultivation and lesser investment. Accordingly, the remaining land can be diversified for other cash crops and agri-entrepreneurship development. Alternatively, if rice cultivation is still continued in 3.2 million hectares, the production can be almost doubled. The same is the case with wheat, where we can enhance the productivity from 2.9 to 5.0 t ha$^{-1}$ with timely sowing and assured irrigation to escape the impacts of terminal heat. With this productivity of wheat, the food demand of the state can be achieved with just 60% of the wheat growing area, and the leftover land can be diversified for other enterprises. Green gram can be best suited in the rice–wheat system, if the provision of timely sowing and assured irrigation is made with the installation of 3-hp single-phase tube wells with submersible pumps.

The results of the study showed that with the assured community irrigation system and shifting planting dates, the productivity of rice–wheat cropping system can be achieved greater than 10.0 t ha$^{-1}$ with a cropping intensity of 300% for better adaptation and sustainable production. Moreover, the water productivity of timely transplanted rice was observed to be 85.8% higher than that of late transplanted one. With the application of our simple innovative technology, the negative impacts of climatic challenges on crop production can be resolved to a large extent in the region for achieving higher productivity of rice–wheat cropping system. However, it is important to assess the impacts of the technology with regard to enhanced farm income, alleviation of rural poverty, and lesser energy utilization. On the other hand, the impact of the technology with respect to groundwater depletion would be a topic for further investigation for upscaling the benefits among the farmers at larger domain.

## 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

RJ: Conceptualization, Investigation, Writing – original draft, Writing – review & editing, Funding acquisition, Methodology, Resources. AbS: Conceptualization, Writing – original draft, Writing – review & editing, Methodology. AnKS: Project administration, Resources, Supervision, Visualization, Writing – review & editing. MK: Investigation, Supervision, Writing – review & editing. RT: Writing – review & editing. AbKS: Writing – review & editing, Investigation, Project administration, Resources. ArKS: Writing – review & editing, Data curation, Investigation, Project administration, Resources. SudhD: Writing – review & editing, Investigation, Project administration, Resources. RP: Writing – review & editing, Investigation, Resources. SKus: Writing – review & editing, Investigation, Methodology, Project administration, Resources. AK: Writing – review & editing, Data curation, Investigation, Resources. MM: Writing – review & editing, Investigation, Methodology, Project administration, Resources. PS: Supervision, Visualization, Writing – review & editing. SG: Writing – review & editing, Investigation, Project administration, Resources. DS: Investigation, Resources, Writing – review & editing. SaR: Investigation, Methodology, Resources, Writing – review & editing. SKG: Writing – review & editing, Investigation, Methodology, Project administration, Resources. RR: Writing – review & editing, Investigation, Resources. RIP: Writing – review & editing, Investigation, Resources. APS: Writing – review & editing, Investigation, Resources. RPS: Writing – review & editing, Data curation, Investigation, Methodology. PKSi: Resources, Writing – review & editing, Investigation, Methodology. PKSr: Project administration, Resources, Writing – review & editing. BJ: Data curation, Supervision, Writing – review & editing. RSe: Data curation, Visualization, Writing – review & editing. SudeD: Data curation, Formal analysis, Writing – review & editing. SS: Data curation, Writing – review & editing. GS: Data curation, Investigation, Writing – original draft, Writing – review & editing. ShR: Data curation, Writing – review & editing. NiK: Data curation, Writing – review & editing. AR: Data curation, Investigation, Writing – review & editing. SaK: Data curation, Resources, Writing – review & editing. VKa: Data curation, Methodology, Resources, Writing – review & editing. SuK: Investigation, Resources, Validation, Writing – review & editing. KC: Data curation, Investigation, Methodology, Writing – review & editing. TK: Investigation, Methodology, Resources, Writing – review & editing. SaP: Investigation, Methodology, Writing – review & editing. AG: Data curation, Resources, Writing – review & editing. AN: Data curation, Investigation, Writing – review & editing. AP: Investigation, Resources, Writing – review & editing. RSi: Investigation, Resources, Writing – review & editing. CR: Data curation, Formal analysis, Investigation, Writing – review & editing. ShP: Data curation, Investigation, Visualization, Writing – review & editing. KR: Data curation, Formal analysis, Validation, Writing – review & editing. SSP: Data curation, Investigation, Writing – review & editing. VKu: Data curation, Methodology, Writing – review & editing. LC: Investigation, Resources, Writing – review & editing. BH: Investigation, Resources, Writing – review & editing. STK: Data curation, Investigation, Writing – review & editing. JS: Data curation, Investigation, Writing – review & editing. SC: Data curation, Investigation, Writing – review & editing. ST: Data curation, Investigation, Writing – review & editing. NaK: Investigation, Writing – review & editing. DT: Investigation, Data curation, 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.

## Publisher's note



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# Opportunities and challenges organo-mineral fertiliser can play in enabling food security

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Food security is a growing challenge related to an increasing global population. The agricultural sector is key for a secure supply of food but relies up to 50% on mineral fertilisers to meet crop nutrient demands. As mineral fertilisers production is energy intensive, causing close to 2% of global greenhouse gas (GHG) emissions, this poses greater challenge to meet net zero targets. Other challenges include extreme weather patterns, GHG during fertiliser applications and diffuse pollution, declining soil health, pest, disease, and loss of soil biodiversity. As mineral fertilisers' price increases and the state of soil health decreases, innovative solutions are needed to meet crop nutrient demands while ensuring that sufficient organic matter is conserved in the soil. One solution to achieve net zero in agriculture can be in the form of organo-mineral fertilisers (OMF). OMFs are a new concept that take organic feedstock (such as biosolids, livestock manure, crop residues, food waste) and combines them with reduced amounts of mineral fertilisers resulting in a balanced fertiliser product. This Perspective piece discusses a Strength-Weakness-Opportunities-Threats (SWOT) analysis on OMF and summarizes how OMF applications can play a role to improve food security. This is further linked with short, medium and long terms policy interventions that can be deployed to achieve a more sustainable approach by balancing between protecting the wider environment and meeting food security.

KEYWORDS

**net zero, circular economy, fertiliser, organic amendments, food security, agriculture**

## Introduction

Continued transformation of the agricultural sector is essential to ensure that sufficient, safe and nutritious food is produced to meet the needs of a growing global population, which is expected to reach 10 billion by 2050 (United Nations, 2019). Agriculture is both a sink and a source of greenhouse gas (GHG) emissions. The OECD has estimated that the agricultural sector can make a net carbon (C) sequestration of 4% of global GHG emissions by the end of the century (Henderson et al., 2022). Coupled with socio-economic development and the need to meet the UN Sustainable Development Goals (SDGs), there is a societal urgency to transition toward a more sustainable food industry, with reduced GHG emissions and increased C-sequestration, while also protecting and enhancing biodiversity, soil health (Pawlett et al., 2021), water resources and air quality. Agricultural activities not only contribute to global GHG emissions but are also responsible for *ca.* 70% of freshwater consumption, loss of biodiversity and declining soil quality (Zhou et al., 2022).

However, the agricultural sector faces many challenges with changing weather patterns and increased climate uncertainty causing severe shocks including increased frequency of extreme rainfall and drought events, new pest and disease risks, and increased levels of soil degradation due to reducing levels of soil organic matter and soil biodiversity (Rickson et al., 2015). To exacerbate the situation, geopolitical instability has resulted in increased volatility and rising energy prices impacting on fertiliser supplies and production costs, and highlighted the risks associated with our dependence on importing key commodities.

While mineral fertilisers are essential to meet nearly 50% of global crop production, its production is energy intensive and causes close to 2% of global greenhouse gas emissions (Menegat et al., 2022). The rapidly increasing population and concurrent food demand escalation is putting increasing pressure on agricultural practices to continually maximize yield. Often, the method by which this is achieved is agricultural intensification. Current practices of intensification rely heavily on mechanization and supplementing the soil with macronutrient fertilisers (such as nitrogen, phosphorus, potassium, and sulfur). Inarguably this trend has led to the general decline of agricultural soil health worldwide, to the point at which the majority of the world's agricultural soils are classed as fair, poor, or very poor (FAO and ITPS, 2015).

With the price of mineral fertilisers increasing and the state of soil health decreasing, solutions are needed to meet crop nutrient demands while ensuring that sufficient organic matter is conserved in the soil. One option can be to use more organic feedstocks, but it needs to be topped up with mineral fertilisers to compensate for any deficiency from it. An innovative solution can be in the form of organo-mineral fertiliser (OMF). OMFs are a new concept that take organic feedstocks such as biosolids, livestock manure, crop residues, food waste and combines them with mineral fertilisers to produce a more desirable nutrient content. The mixture is then dried and pelleted to make it easily storable and transportable. The concept behind OMF is to couple the slow and fast release patterns of organic feedstock and mineral fertiliser, respectively, to minimize reliance on the latter. While this concept is still in its infancy, Deeks et al. (2013), Pawlett et al. (2015), and Antille et al. (2017) have pioneered on OMF using biosolids as feedstock. Burak and Sakrabani (2023) reported novel approaches in formulating OMF using carbon capture technology resulting in fertilisers which resulted in crop yield comparable to mineral fertilisers. This recycling of organic waste promotes a circular economy and provides a sustainable source of nutrients that will both feed the crops and act as a tool for the re-introduction of organic matter into agricultural soils (Sakrabani et al., 2023).

The current challenges faced globally due to extreme weather conditions, increasing cost of energy and soil degradation, all directly affects food security. Tackling food security is vital to address the increasing global population. Circularity in use of resources is key in sustainability and this article adopts this approach and will set the way to a new approach that adopts technology to turn underutilized resources (such as manure, crop residue, digestate) into valuable products such as organo-mineral fertilisers (Sakrabani et al., 2023). This Perspective article covers agriculture, crop and soils, natural environment, food security and the wider landscape. It also touches on aspects related to the SDGs to improve land quality, minimize hunger by providing food security, climate action, industry and innovation. This Perspective article presents a forward-looking net zero vision and approach on how to valorize organic resources using nature-based solutions while using technology and minimize reliance on processes that pose greater harm to the environment. The aim is to present an outlook on how OMFs can be considered as part of the toolbox to tackling some of the challenges and what will the opportunities and challenges pose in implementing sustainable agriculture.

## Approach

The approach of this Perspective article is in the form of a framework for a Strength Weakness Opportunities and Threat (SWOT) analysis as shown by Figure 1. The SWOT analysis will be used as means to link each section to debate how OMFs can play a role in implementing sustainable agriculture while tackling food security. The challenges highlighted in earlier section will be categorized into short, medium and long term and the SWOT will be used to match where possible to assess how feasible will be the various options to tackle the challenges.

The *strengths* of using OMF shows potential to increase soil organic matter and water holding capacity (Oliveira et al., 2017; Moreira et al., 2021; Kumar et al., 2022). There has been evidence to reduce soil compaction through decreasing bulk density, allowing good transport of water and nutrients. The carbon content of the feedstocks used to formulate OMFs can be important for improving soil health, allowing soil microbial proliferation which facilitates residual nutrient mineralization for subsequent seasons (Semida et al., 2014; Mumbach et al., 2020). Due to the on-going challenges in increasing fertiliser prices, there is a growing need to ensure sustainable sources of fertilisers are available in order not to compromise on food security (Mazeika et al., 2021). Nevertheless, currently as OMF is a new approach in agriculture allowing circular economy approach, it may not necessarily fetch a lower price as it will need new technologies to process the feedstock, dry and pelletize it. However, with more development in such technologies and better logistics of getting the feedstock, there is a possibility that prices can become more competitive. There is a real need for innovative techniques and optimizing existing ones to valorize organic feedstock to make OMF more mainstream products in agriculture.

The nutrient composition of organic feedstock is usually imbalanced, i.e., N:P ratio, where application based on one nutrient will cause under application of the other. This is where in OMF, the mineral part tackles nutrient imbalance, making it a balanced fertiliser product. The carbon sources of OMF feedstock can also potentially contribute to carbon sequestration, albeit being slow depending on soil type, crop, land management and climate. Activities that can sequester carbon have been claimed to enhance soil fertility, increase soil biodiversity, improve water retention and reduce runoff and erosion (Smith, 2012). There are claims that soil carbon sequestration would be able to support five, seven and up to 12 SDGs (Smith et al., 2019). However, Moinet et al. (2023) argue that soil carbon sequestration is context specific and there is a saturation point (after 20 years as standard or ranging from 5 to 50 and up to 85 years) and non-permanence which needs to be seriously considered. In this context, any potential carbon build-up related to applications of OMF needs to be accurately quantified for its permanence. This is an important consideration, due to potential remuneration options for farmers in terms of carbon credit. While there is limited information assessing the carbon credit potential of OMFs, Paul et al. (2023) highlight the following as principles that must be considered to close

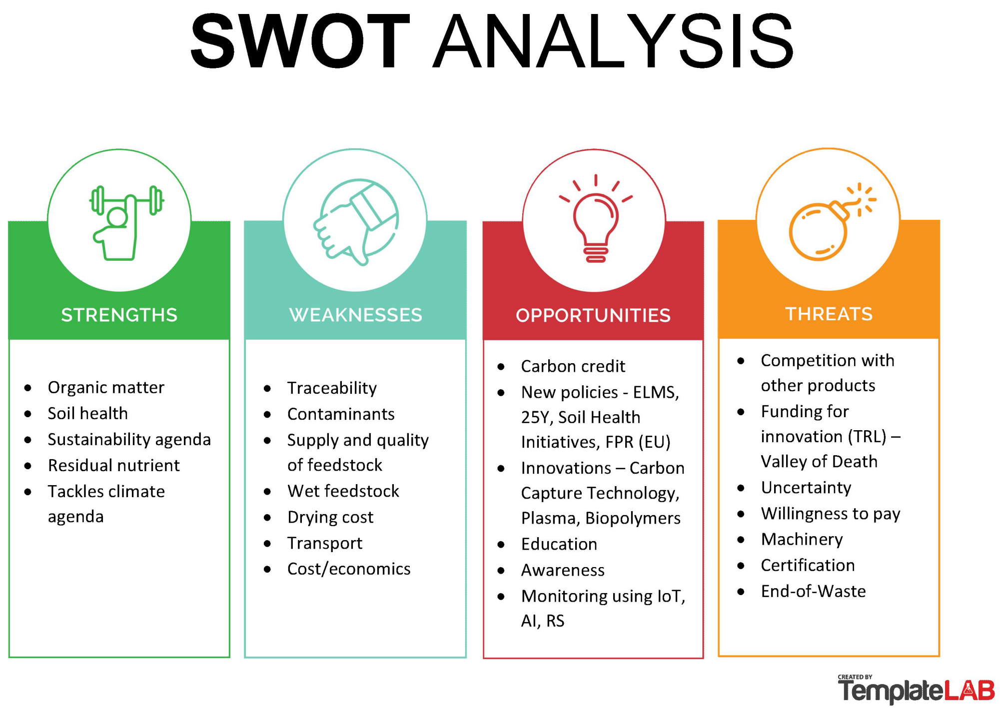


FIGURE 1
SWOT analysis of utilizing OMF in agriculture. EMLS, Environmental Land Management Systems; FPR, Fertiliser Products Regulation; IoT, Internet of Things; AI, artificial intelligence; RS, remote sensing.

this knowledge gap: additionality, emission reductions, permanence, quantification of soil organic carbon changes, leakage effects, synergies and trade-offs, and transparency, legitimacy, and accountability. Strict regulatory procedures need to be implemented to ensure farmers are protected and properly remunerated for actions related to making soil carbon sequestration more permanent.

The *weaknesses* of using OMF can be related to traceability due to variability of feedstocks used to formulate it. Gathering evidence on how to quantify the variability of nutrient content will provide confidence on OMF applications. There is on-going work on in-field technology using near and mid-infrared sensors that can be developed to determine nutrient content of organic feedstocks (Barra et al., 2021). There is also a need to ensure that contaminants of feedstocks are controlled so that the final product can be suitably applied in agriculture. A control of contaminants at source is the best way to manage this challenge. Depending on the organic feedstocks, control of these contaminants can be managed differently. Levels of contaminants in biosolids such as organic compounds (flame retardants) or microplastics are more challenging to control compared to heavy metals where there is the Sewage Sludge Directive (Egle et al., 2023) that provides limits that cannot be exceeded. Feed additives containing trace elements such as Cu and Zn can be cause for concern when present in animal manure (Bünemann et al., 2024). This is essential to not only minimize accumulation of these heavy metals but also its potential impact to form stable complexes with soil organic matter which can promote antimicrobial resistance (Bengtsson-Palme et al., 2023). However, on-going regulatory framework by governments will lead to lower inputs of these elements in the future.

In terms of nutrient content, some organic feedstocks are not in readily available forms but instead in more slow-release forms. This slow-release nutrient supply coupled with a mineral fertiliser will be a win-win solution if it is matches with crop demands at its key crop growth stages. This slow-release feature ensures a more gradual and sustained nutrient release, reducing the risk of nutrient leaching and runoff. It helps plants receive a continuous supply of nutrients over longer period, leading to better nutrient use efficiency and minimizing the potential for nutrient imbalances or wastage (Semida et al., 2014). However, what makes it challenging is we need to source a large amount of organic feedstock to meet crop requirements in a timely manner. These feedstocks also tend to have a high moisture content (10–20% for crop residue, 80–90% for biosolids and manure) (AHDB, 2023) which requires drying to reduce its bulk. This naturally increases cost due to energy needed for partly drying the feedstock. If the energy for drying can be from renewable sources (i.e., solar, biomass), then this makes it more sustainable as otherwise it increases the cost. Reducing the bulk of the feedstock also allows for ease of transportation from source to locations where it will be needed. The cost benefit must be considered to ensure what type and how much energy is needed to dry the feedstock to formulate OMFs. Techno-economic analysis will need to be carried out to have a holistic view on cost implications resulting from drying feedstock and its impact on the final price of OMFs to farmers.

The *opportunities* for using OMF can be capitalized by increasing innovations such as carbon capture (Burak and Sakrabani, 2023), plasma, super critical oxidation technologies among some of them to valorize organic amendments. Each of these technologies has its advantages and disadvantages and needs to be used where suitable to optimize use of organic amendments. Technologies such as artificial intelligence, remote sensing and Internet of Things (IoT) can be very valuable in collating data on soil health and crop productivity associated with application of OMFs. The impact of OMF application on soil and crops requires long-term trials and use of such technologies is particularly important to enable more regular monitoring compared to conventional approaches. To enable any new technologies and interventions it must be accompanied with an awareness or educational campaign. There will be some skepticism and reluctance to use any new product or technology until there is confidence in its use. This can create opportunities for gathering scientific evidence and communicating about it to relevant stakeholders.

On aspects related to traceability highlighted earlier, there is on-going work using novel technologies such as neutron tomography and muonic X-rays to assess heterogeneity within OMF pellets. As OMFs involve organic feedstock of varying quality, how these are packed within a pellet is important to assess how it can be evenly spread and breakdown to release nutrients. As an example, neutron tomography can determine extent of moisture levels of the constituents within each pellet which will inform how it will disperse when subjected to a force such as that from a fertiliser spreader spinning disc. Muonic x-rays involves a non-destructive technique capable of determining key elemental composition at various depths within a pellet. These information on particle arrangements within a pellet is also important to inform on response to moisture absorption (determined by neutron tomography) and how it will influence it to disintegrate and release nutrients and elements (determined by muonic X-rays) when in contact with soil.

Current policy drivers such as the Environmental Land Management Systems (ELMS), Soil Health Action Plan for England (SHAPE), Defra 25 Year Environmental Plan and new UK Fertiliser Products Regulations (derived from the EU), promote proper use of organic resources to improve soil health and minimize reliance on mined sources of material to ensure sustainability is firmly embedded in practice. In Europe similar policies such as the Fit for 55 package, the Zero Pollution Action Plan and the EU Soil Strategy for 2030 all aim to protect soil as part the EU Green Deal (Panagos et al., 2022).

The *threats* related to use of OMF can be associated to competition from other amendments such as compost, digestate, animal manure, crop residues and biosolids which are widely used and have more credibility in the agricultural sector. When using new products such as OMF, there is also a need to assess the willingness to pay for it, due to uncertainty on its efficacy. There is also a need to ensure the OMFs do not require new machinery as farmers will be reluctant to invest in new equipments for products which are not well understood. Using new products such as OMF will also be subject to regulatory restrictions to ensure that it is not classed as a waste and requires End-of-Waste status. To achieve this, there needs to be evidence that is a product and is comparable to existing options that are being used in the sector.

## Forward outlook considering policy aspirations

National and international policies are key to implement application of OMF in agriculture but require robust scientific evidence to ensure that it is a product and not classed as waste. This will not be easily achieved if there is no clear drive and vision and short-, medium- and long-term policy interventions are briefly discussed here.

In the short term there needs to be a clear definition and guidelines on what is a suitable comparator to existing OMFs to gather the evidence needed for it to reach End-of-Waste status. The evidence gathered will be on OMF characteristics and should be within the allowed legal guidelines for target parameters. There needs to be energy incentives for drying feedstocks so that a sustainable business case is feasible for processing of feedstock. The approach for drying will be targeted on feedstock which are semi-solid such as composted material or manure mixed in with straw. These will still contain lower amount of available N, so there needs to be some caution for losses as ammonia. Policy incentives for provision of renewable sources of energy will be well suited to incentivize processing of feedstock to produce OMFs. These incentives will also influence the final price of OMFs making it more affordable and available to farmers. There should also be strict policy interventions (e.g., Sewage Sludge Directive as discussed by Egle et al., 2023) to ensure contaminant levels of organic feedstock such as biosolids adhere the safe threshold levels as this will influence the quality of OMFs and finally impact on soil health.

In the medium term there needs to be collation of evidence from longer term field trials. This is necessary to ensure impact of OMFs on soil and crops can be monitored as nutrient release patterns are much slower compared to mineral fertilisers. The available technologies need to be cost effective so that feedstock can be valorized and be suitable to formulate OMFs. Innovations associated with technologies suffer from funding challenges especially in mid-range Technology Readiness Level (TRL) (Figure 1) which needs funding boost to make it viable in the market. The lack of funding at these TRLs sometime can be seen as missed opportunities and policy interventions are necessary to mitigate this (Sakrabani, 2023). Policies also tend to be regional and there needs to be harmonization especially when there can be potential transportation of OMFs from one part of the country to another. If an organic feedstock component of the OMF is not classed as waste, then it will cease to be a product and when it will be transported to another country or region which operates using different legislation, this can cause problems for applications in agriculture. This lack of harmonization can limit the full use of OMFs, and rigorous paperwork is needed to enable easier transportation of OMFs. The paperwork can have information on location of feedstock origin, composition of feedstock and its characteristics (physical, chemical and biological) and volume. These will provide traceability and lead toward greater confidence when OMFs will be transported between regions.

In the longer term there needs to be certification so that feedstock can be fully valorized and validated to become products marketed as OMFs. The initial steps required for the certification will be liaison with institutions such as the British Standards Institution (UK), European Committee for Standardization (Europe) or International Organization for Standardization (International). There are dossiers which needs to be developed for OMFs on its nutrient and contaminants (chemical and biological) contents and its variability. In these dossiers the ranges of nutrients and contaminants including corresponding analytical methods will be highlighted. Limits for the ranges of parameters will be corroborated with conventional fertilisers currently used in agriculture, considering feedstocks that constitute the OMFs. There will be an expert Panel committee which will validate the data and information presented in the dossier leading toward obtaining the certificate. This requires some joint up approach between waste and fertiliser regulations and harmonizing to ensure successful implementation of OMF applications in agriculture to meet food security and maintain soil health.

## Conclusion

There is clearly a need to consider OMF as part the solution to reduce reliance on mineral fertiliser requirements to meet crop demands. OMF is not a panacea and has its own challenges in terms of traceability, its nutrient content to meet crop demands, moisture content of feedstock and the need to dry as pellets or granules it to make easier to handle. Innovation is key in acting as a conduit to mitigate some of the challenges to valorize organic feedstock. However, policy interventions are key to address any potential barriers. Consequently, this Perspective piece sets an outlook on how based on the SWOT analysis, short, medium- and long-term policy aspirations can be achieved by implementing use of OMFs in agriculture to attain a net zero and sustainable approach while balancing between protecting the wider environment and meeting food security.

## 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/s.

## Author contributions

RS: Conceptualization, Funding acquisition, Investigation, Methodology, Writing – original draft, Writing – review & editing, Resources, Visualization.

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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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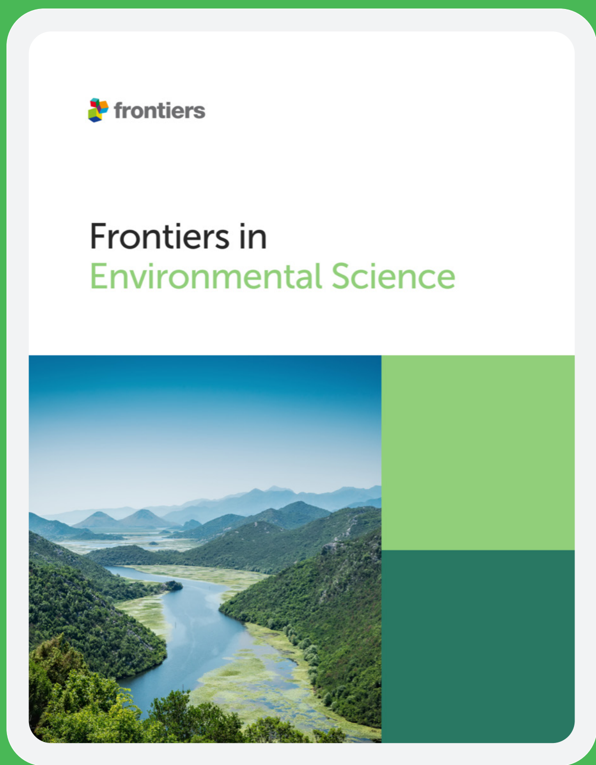


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