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Genetic diversity and climate change adaptation in wheat: a systematic review of landraces, composite cross populations, and evolutionary populations

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Introduction: Climate change adaptation is a growing priority in global agriculture due to its threats to cereal crops like wheat. In this context, wheat landraces, composite cross populations, and evolutionary populations, developed through evolutionary plant breeding, are increasingly recognized for their genetic diversity and contributions to agrobiodiversity. These populations offer promising pathways for improving drought tolerance, yield stability, and resilience, particularly in organic farming systems. However, a comprehensive synthesis of their role in adapting wheat to climate change remains limited.

Methods: This systematic review followed PRISMA guidelines to identify and evaluate studies on wheat landraces, CCPs, and EPs in the context of climate change adaptation. A comprehensive search was conducted across five databases (Web of Science, Scopus, ScienceDirect, iScience, and Google Scholar) for studies published between 2011 and July 2024. Inclusion criteria focused on empirical studies addressing climate adaptation, evolutionary plant breeding, and wheat diversity. A modified CASP tool was used for quality assessment, and thematic synthesis was performed.

Results: Thirteen high-quality studies were included from an initial pool of 325 records. The findings indicate that wheat landraces, CCPs, and EPs outperform modern varieties in yield stability, drought tolerance, disease resistance, and nutritional quality, especially in organic and marginal farming systems. EPs showed strong yield consistency and adaptability; landraces exhibited high drought tolerance and grain quality; and CCPs offered buffering capacity under biotic and abiotic stresses. However, most studies were concentrated in Europe, and gaps were found in farmer adoption research, post-harvest traits, and geographic representation.

Discussion: Wheat landraces, CCPs, and EPs are vital for developing climate-resilient wheat varieties and sustainable food systems. Their integration into breeding programs can enhance crop adaptability in the face of climate change. Nonetheless, broader research in diverse agroecological zones and greater attention to socio-economic and post-harvest factors are needed. This review highlights the strategic role of genetic diversity in wheat for building resilient agri-food systems and outlines directions for future research and policy.

KEYWORDS

climate change adaptation, wheat landraces, composite cross populations, evolutionary populations, evolutionary plant breeding, genetic diversity, drought tolerance, yield stability

Introduction

Climate change consists in the sustained alteration of the Earth's global temperature and weather patterns. These changes mark the evolutionary history of the Earth system and can be traced back to several factors, including biotic processes, variations in the solar radiation received by the Earth, plate tectonics and volcanic eruptions (Pielke, 2004). However, since the mid-20th century, the speed of these changes increased regarding global temperatures and the frequency of extreme weather events such as droughts, intense hail, temperature anomalies, tornadoes, floods and storms (Seneviratne et al., 2021). Decades of research and peer-reviewed studies showed that human activities, ranging from the extraction, production and consumption of fossil fuels and other industrial processes to intensive agriculture, with their excessive greenhouse gas emissions, are primarily responsible for these abrupt changes (Intergovernmental Panel on Climate Change, 2021).

Climate change leads to severe economic and social disruptions, also impacting health, biodiversity, and agricultural systems as well. Regarding the impact on the latter, factors such as water availability, temperature and atmospheric CO_2 can impair cereal yield and grain quality by affecting plant growth processes and defense mechanisms, the biology of plant pathogens and their interaction with host plants (Elad and Pertot, 2014). The increasing frequency and intensity of climatic events are expected to cause significant yield losses for many crops (Senapati et al., 2021). The challenge, therefore, is to ensure food production that meets global food security needs through, probably, multiple approaches (Food and Agriculture Organization, 2022).

According to Pequeno et al. (2021), addressing this challenge requires the adoption of two strategies considered both essential and of highest priority. One consists of a strong mitigation strategy to globally reduce greenhouse gas emissions; the other concerns the need to develop adaptation strategies, which involve the capacity to simultaneously diversify both the types of crops and the methods of cultivation (Howden et al., 2007; Food and Agriculture Organization, 2023).

Wheat *(Triticum spp.)*, belonging to the Poaceae family is, after maize and alongside rice, one of the most important cereal crops in the world (Ritchie et al., 2023). It is widely cultivated on a global scale, from temperate to subtropical regions, and serves as a staple food in many countries. The main wheat species are *Triticum aestivum* (common or bread wheat) and *Triticum durum* (durum wheat): the former, which dominates global wheat production, is primarily used for breadmaking due to its high gluten content (He et al., 2019), while the latter, mainly used in pasta production, is known for its hard texture and high protein content (Maccaferri et al., 2019).

Modern wheat varieties are genetically uniform cultivars bred through intensive breeding programs to achieve high yields and consistent performance in optimal, high-input agricultural systems (Dawson et al., 2011). However, their narrow genetic base makes them vulnerable to environmental stresses such as drought, pests, and diseases—factors expected to become more frequent and severe due to climate change (Reynolds and Langridge, 2016).

Based on recent studies (Lobell and Di Tommaso, 2025; Asseng et al., 2019; Liu et al., 2021), the global challenges in wheat production due to climate change concern different aspects such as yield reduction, regional impacts on yield production, interannual variability, and nutritional quality.

By linking agroclimatic data to crop productivity, Lobell and Di Tommaso (2025) estimated that current global yields of wheat, maize, and barley are 10%, 4%, and 13% lower, respectively, than they would have been without the influence of climate trends. The impact of this reduction varies across regions, with significantly more severe consequences in already arid and economically disadvantaged areas, where the lack of infrastructure and adaptive capacity hinders effective responses to climate stressors.

Elevated atmospheric carbon dioxide (CO_2) levels, a consequence of climate change, have been shown to adversely affect the nutritional quality of staple crops like wheat. Specifically, increased CO_2 concentrations can lead to reductions in essential nutrients such as protein, iron, and zinc in wheat grains, posing significant risks to global food security and human health (Myers et al., 2014).

One of the main areas of response to these challenges lies in genetic research, which focuses both on the development of crop varieties with different maturation timings, allowing better adaptation to changing climatic conditions—and on the identification and introduction of genetic traits (Balfourier et al., 2019) that enhance resistance to drought, diseases, and pests (Würschum et al., 2020).

However, regarding the replacement of early-maturing varieties with late-maturing ones, Zhang et al. (2022) emphasized that, although this strategy is widely adopted in climate scenario simulations, it remains largely theoretical. Relying solely on the extension of the crop growth period oversimplifies real-world conditions and fails to fully capture the complex and multifactorial nature of crop adaptation to climate change.

Broadly speaking, what we have learned from evolutionary theories is that the survival and long-term success of species depend on their capacity to adapt to changing environments, a process driven by natural selection acting on genetic variation. Populations with greater genetic and phenotypic diversity are more likely to include individuals with traits suited to new or shifting conditions, thereby increasing the likelihood of persistence and evolutionary resilience over time.

This variability can still be found in traditional wheat cultivation, that is, in crop populations maintained before the advent of intensive agriculture and the agro-industrial model. These traditional or landrace varieties often retain a broad genetic base, shaped by centuries of adaptation to diverse local environments, farming practices, and selective pressures, making them valuable reservoirs of traits for resilience and adaptability.

These varieties have not undergone modern breeding processes and are characterized by a high level of genetic diversity and phenotypic expression (Zeven, 1998). Their relevance lies in their long-term adaptation to both biotic and abiotic stresses, making them particularly suitable for marginal or low-input conditions (Dwivedi et al., 2015). Beyond their agronomic value, landraces are also linked to cultural heritage and traditional farming practices (Veteläinen et al., 2009), and their integration into modern breeding efforts has been discussed as a way to improve resilience to climate change (Louwaars, 2007; Reynolds et al., 2009; Tadesse et al., 2019).

Discussions around the role of landraces in mitigating climate change also highlight their efficiency in resource use and their contribution to agrobiodiversity. Their lower dependence on external inputs such as fertilizers or pesticides, due to environmental adaptation, may support more sustainable farming systems (Zhu et al., 2000; Food and Agriculture Organization, 2010). These qualities are increasingly cited in arguments for their conservation and use in climate-resilient breeding strategies (Ceccarelli et al., 2010).

While landraces are traditional, locally adapted wheat populations that have evolved over centuries through natural processes and unconscious selection by farmers, composite cross populations (CCPs), first conceptualized by Harlan and Martini (1929) and further developed by Suneson (1956), represent the first scientific attempt to mimic such evolutionary processes. CCPs are established by inter-crossing numerous genetically diverse parents, bulking the resulting F1 seeds, and allowing the population to evolve in the field under natural selection without further artificial intervention.

Building on the conceptual foundation of CCPs, evolutionary populations (EPs) extend these principles from a primarily experimental context to a practical, farmer-centered framework. EPs are intentionally designed to evolve continuously under both natural and farmer-mediated selection, particularly within low-input, organic, and participatory agricultural systems (Döring et al., 2011). While CCPs emphasize the initial creation of genetic diversity, EPs prioritize its maintenance and dynamic evolution over time, adapting to changing environmental and socio-economic conditions.

Together, landraces, CCPs, and EPs represent a continuum of *in situ* evolutionary approaches to crop development. Despite their differences in origin and management, they share a fundamental logic: that genetic diversity and evolutionary potential are key to crop resilience and adaptability, especially in the face of climate change and the transition toward more sustainable agricultural systems (Dawson et al., 2011).

In recent years, EPs, particularly in barley and wheat, have drawn attention as alternative approaches to conventional crop development, especially under organic and low-input systems. These populations are being explored for their potential role in resilient farming systems and are increasingly associated with participatory and decentralized breeding strategies that involve farmers in ongoing selection cycles (e.g., Salimi et al., 2023; Raggi et al., 2017; Weedon et al., 2023; Ceccarelli and Grando, 2024). While some of these works may be included later in this review, they are referenced here strictly to provide background and illustrate the growing interest in evolutionary breeding as a climate-adaptive strategy.

The broader potential of wheat landraces, CCPs, and EPs, to contribute to food security and climate change adaptation is increasingly acknowledged in the literature (e.g., Okazaki et al., 2021). However, much of the evidence remains dispersed across various ecological settings, breeding methodologies, and research aims. A systematic review is therefore needed to consolidate existing knowledge, clarify the role of these populations in climate adaptation, and identify gaps that merit further exploration.

This systematic review building upon prior work (Döring et al., 2011) offers an updated and integrative analysis on the role of landraces, Composite Cross Populations (CCPs) and evolutionary populations (EPs) in wheat breeding, in the context of climate change adaptation and mitigation.

Unlike prior reviews or fragmented studies that focus on isolated breeding approaches or geographic contexts, this review synthesizes findings from diverse agro-ecological settings and management systems to evaluate the adaptive traits of wheat landraces, CCPs, and EPs.

By systematically categorizing research justifications and quantifying adaptation traits, including yield stability, biotic stress resistance, and drought tolerance, this review provides a robust comparative analysis of wheat landraces, CCPs, and EPs, relative to modern wheat varieties.

This systematic review aims to contribute directly to the development of climate-smart food systems by synthesizing evidence on the adaptive potential of wheat wheat landraces, CCPs, and EPs, in response to climate change. By examining how genetic diversity and evolutionary plant breeding approaches enhance crop resilience, particularly under low-input and organic systems, this review aligns with the core objectives of climate-smart agriculture: improving food security, promoting sustainability, and increasing the adaptive capacity of farming systems. This study aims to contribute methodologically and contextually to the understanding of the capacity of wheat landraces, CCPs, and EPs, in the adaptation and mitigation of climate change, highlighting how genetic heterogeneity in wheat can be strategically harnessed for climate-resilient agricultural development. This study reviews and synthesizes relevant studies' contents and thereby provides a broader assessment of their adaptation capacity to climate change. Moreover, aims to identify gaps in the current literature and provide recommendations for future research direction. The findings will provide critical insights for researchers, breeders, and policymakers working to design resilient, diversified, and regionally adapted food systems in the face of growing climate variability.

Research questions

1. What are the main objectives and justifications of the research conducted on wheat evolutionary population and landraces in relation to climate change?
2. What is the adaptation capacity to climate change of the wheat landraces, CCPs and Eps?
3. What are the gaps in the current literature on the subject matter and relevant recommendations for future research directions?

Research objectives

1. To perform an analysis of the objectives and justifications of the included studies on wheat landraces, CCPs and Eps and climate change.
2. To evaluate their adaptation capacity on climate change amongst the studies included in this review.

3. To identify gaps in the current literature and provide recommendations for future research directions.

Materials and methods

Study design

This systematic review follows the protocol Preferred Reporting Items for Systematic Review and Meta-Analysis Protocols (PRISMA). The PRISMA guidelines provide items informed by empirical research for systematic reviews and meta-analyses (Page et al., 2021).

Eligibility criteria

In line with the objectives of this research, studies were eligible for inclusion if they met the following criteria:

i) Investigated landraces of wheat, composite cross populations or evolutionary populations.
ii) Addressed challenges related to climate change in wheat cultivation.
iii) Provided data on wheat ecotypes.
iv) Included information on evolutionary plant breeding techniques.
v) Discussed strategies for mitigating the effects of climate change.
vi) Published in English.

Studies were excluded if they:

i) Focused on plant species other than wheat.
ii) Examined solely wheat varieties developed through breeding techniques other than evolutionary plant breeding.
iii) Had titles or abstracts that did not explicitly address the topic of interest.
iv) Discussed climate change mitigation measures unrelated to wheat cultivation.
v) Focused exclusively on human participation in climate change mitigation.
vi) They were not available in full text.
vii) Were published before 2011.

Information sources and search strategy

A comprehensive search was conducted across the following databases: **Web of Science**, **Scopus**, **ScienceDirect**, **iScience**, and **Google Scholar**. The period of literature search was set from the year 2011, which was the year the last review was published on the topic (Döring et al., 2011), The final search was completed on **July 8, 2024**.

Search strategies combined keywords and Boolean operators ("AND") were applied to optimize retrieval. The search terms included: "Wheat Landraces AND Climate Change", "Wheat Composite Cross Populations AND Climate Change", "Wheat Evolutionary Populations AND Climate Change", and "Wheat Evolutionary Plant Breeding AND Climate Change".

Selection process

Two independent reviewers (KB and NM) screened titles and abstracts according to the eligibility criteria. In cases of disagreement, a third group of reviewers (SC, GG, and MG) was consulted to reach consensus.

All identified articles were exported into a dedicated database to remove duplicates. The number of articles retrieved, screened, excluded, and included was documented following the PRISMA flow diagram (see Figure 1).

Following the initial screening phase, the remaining articles underwent a rigorous manual assessment and were systematically coded using a pre-specified eligibility adjudication grid. This grid recorded not only standard bibliographic metadata (e.g., publication date, title, and authorship) but also critical study descriptors, including the specific type of wheat analyzed, the primary research aims, the extent to which climate change was identified as a central concern for wheat cultivation, and the geographical context of the research activities.

This stage facilitated a further refinement of the study selection process, ensuring strict adherence to the predefined eligibility criteria and enhancing the methodological rigor of the review. Subsequently, eligible studies proceeded to structured data extraction and thematic synthesis. Data were systematically organized to allow for an in-depth thematic analysis, with particular emphasis on identifying emergent patterns related to the role of evolutionary populations and landraces in enhancing wheat resilience to climate variability, documenting methodological heterogeneity, and mapping research gaps across the corpus of included studies.

Quality assessment

The Critical Appraisal Skills Programme Tool for Qualitative Research (CASP) was used to assess the quality of the studies included in the review. The tool consists of 10 criteria that evaluate a study's methodological rigor and validity (Critical Appraisal Skills Programme (CASP), 2018). A rating approach was used to determine relative study quality (Long et al., 2020). Studies were classified as 'high quality' if they satisfied at least eight of the ten criteria, 'moderate quality' if they met 5–7 of the criteria, and 'poor quality' if they met four or less. This tool was tweaked to suit the interest of this review and the included studies.

Data synthesis

Given the heterogeneity in study design, measures employed, and outcomes reported, a narrative synthesis approach was adopted, following the framework outlined by Popay et al. (2006).

Thematic synthesis focused on identifying recurring patterns concerning the contribution of evolutionary populations and landraces to wheat adaptation under climate change, documenting methodological variability, and highlighting research gaps across the included studies.

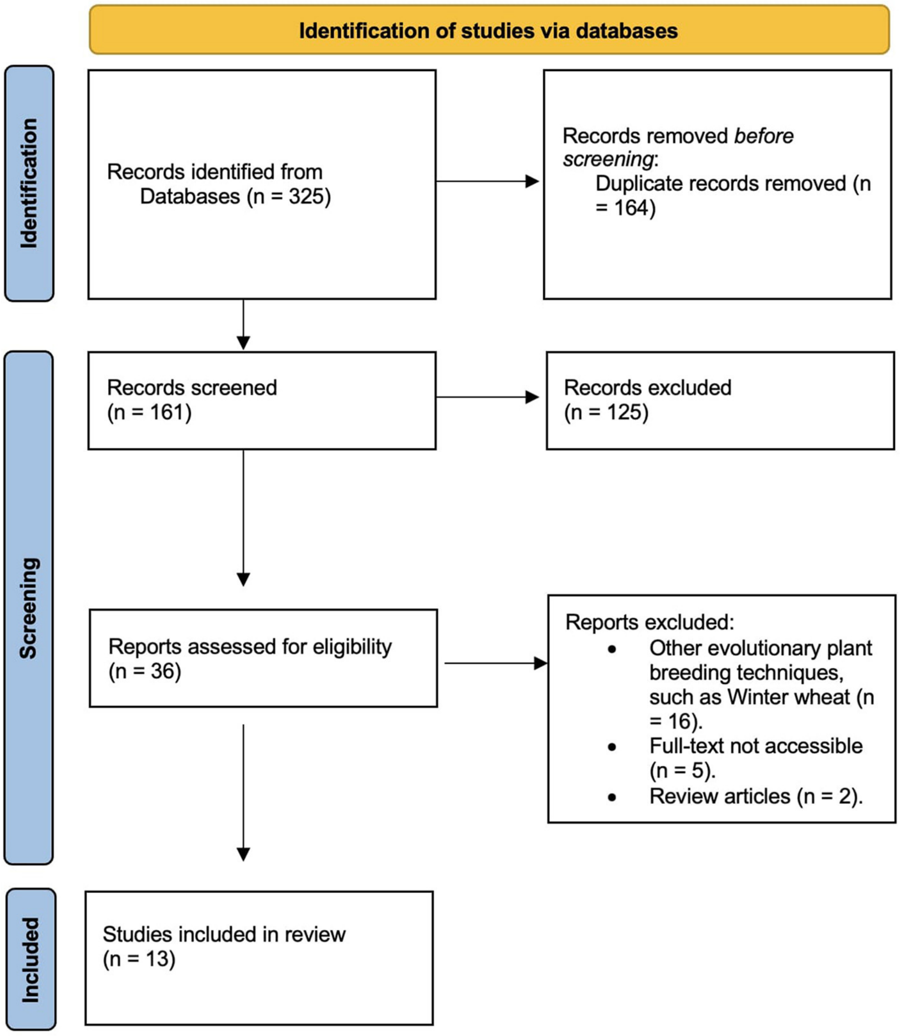

FIGURE 1
PRISMA 2020 flow diagram of included studies.

Results

Properties of studies included in this systematic review

Articles identified

A total of 325 records were initially identified through database searches. After deduplication, 164 records were excluded, while 161 records were selected for screening.

Following title and abstract screening, 125 records were excluded, and 36 records were assessed for eligibility.

The full texts of 36 articles were then assessed for eligibility. Of these, 23 articles were excluded for the following reasons:

- Focused on other evolutionary plant breeding techniques, such as Winter wheat ($n = 16$);
- Full-text not accessible ($n = 5$);
- Review articles ($n = 2$).

Ultimately, 13 studies met the eligibility criteria and were included in this systematic review. The study selection process is summarized in the PRISMA flow diagram (Figure 1), and the 13 articles selected are summarized in Table 1.

Justification for the number of included studies ($N = 13$)

This systematic review includes 13 primary studies, which may seem limited and modest. However, this reflects the rigorous methodology applied during the study selection process, which adhered strictly to the PRISMA protocol. The search period was intentionally set to begin after the publication of Döring et al. (2011), a seminal review in the field, to prioritize new empirical contributions that build on earlier conceptual work. The review's cut-off date was the last day the search was conducted, 8th of July 2024, and it ensures that the included studies reflect the most recent decade of research.

TABLE 1 Summary of selected articles.

Author	Title	Research location	Scope of research	Type of research	Key focus
Abu-Zaitoun et al. (2018)	Unlocking the genetic diversity within a Middle-East panel of durum wheat landraces for adaptation to semi-arid climate	Lab at Volcani Center (Bet Dagan), Field trials near Gilat Research Center, Negev, Israel	Landraces	Lab and field experiment	Genetic diversity and adaptation to semi-arid climate
Baresel et al. (2022)	Performance and evolutionary adaptation of heterogeneous wheat populations	Organic Experimental Station Neu-Eichenberg, Hesse, Germany	EPs	Field experiment	Evolutionary adaptation in wheat
Bocci et al. (2020)	Yield, yield stability and farmers' preferences of evolutionary populations of bread wheat	Multiple farms across Tuscany and Umbria, Italy	EPs	Field experiment	Yield stability and farmer preferences
Brumlop et al. (2017)	Evolutionary effects on morphology and agronomic performance of three winter wheat composite cross populations	Organic Research Station, Neu-Eichenberg, Hesse, Germany	CCPs	Field experiment	Effect of organic vs. conventional farming
Carranza-Gallego et al. (2019)	Addressing the Role of landraces in the sustainability of Mediterranean agroecosystems	Catalonia region, Spain	Landraces	Field experiment	Role of landraces in Mediterranean agroecosystems
Colombo et al. (2022)	Agriculture in marginal areas: reintroduction of rye and wheat varieties for breadmaking in the Antrona Valley	Terraced fields, Antrona Schieranco, Antrona Valley, Piedmont, Italy	EPs	Field experiment	Reintroducing traditional cereals
Dodig et al. (2012)	Comparison of responses to drought stress of 100 wheat accessions and landraces	Institute of Field and Vegetable Crops, Novi Sad, Serbia	Landraces	Field experiment	Drought tolerance screening
Döring et al. (2015)	Comparative analysis of performance and stability among composite cross populations	Wakelyns Agroforestry, Suffolk, UK	CCPs	Field experiment	Stability of CCPs and variety mixtures
Merrick et al. (2020)	Utilization of evolutionary plant breeding increases stability and adaptation of winter wheat	Montana State University (Bozeman) and Washington State University (Pullman), USA	EPs	Field experiment	Adaptation across precipitation zones
Migliorini et al. (2016)	Agronomic and quality characteristics of old, modern and mixture wheat varieties and landraces	Santa Maria a Monte (Pisa) and Arezzo, Tuscany, Italy	Landraces	Lab and Field experiment	Agronomic and quality traits under organic farming
Mohammadi et al. (2015)	Field evaluation of durum wheat landraces for prevailing abiotic and biotic stresses	Highland rainfed areas, Kurdistan Province, Iran	Landraces	Field experiment	Stress resistance in durum wheat
Weedon et al. (2023)	High buffering potential of winter wheat composite cross populations	Wakelyns Agroforestry, Suffolk, UK	CCPs	Field experiment	Yield buffering against rapid climate change
Weedon and Finckh (2019)	Heterogeneous winter wheat populations differ in yield stability	Wakelyns Agroforestry and other organic farms, Eastern England, UK	EPs	Field experiment	Yield stability linked to genetic background and management

In addition, only original, full-length, peer-reviewed articles were included, while review papers, conceptual discussions, and inaccessible full texts were excluded. The scope was strictly confined to studies examining wheat evolutionary populations (EPs), landraces, or composite cross populations (CCPs) in the context of climate change adaptation or mitigation. Studies focusing on other crops, conventional breeding lines, or unrelated mitigation strategies were systematically excluded, which further constricted the volume of eligible articles to be selected.

The relatively small number of studies thus reflects both the specificity of the research focus and the stringent inclusion criteria, ensuring that only the most thematically relevant and methodologically rigorous studies were synthesized. This methodological rigor enhances the credibility, depth, and precision of the review's findings, even with the modest sample size. The studies included in this review represent the most robust and thematically aligned evidence currently available, providing a focused and high-quality synthesis of the research on wheat adaptation to climate change.

Study descriptions

The studies included in this systematic review covered a range of 11 years from 2012 to 2023. There was one article per year, except in 2013. In the years 2020 and 2022, there were 2 studies each.

Quality assessment

Quality appraisal was conducted using the Critical Appraisal Skills Programme (CASP) checklist:

- 4 studies achieved a full score of 10 stars;
- 6 studies received 9 stars;
- 3 studies received 8 stars.

Overall, all included studies were classified as high quality. Details of the quality assessment are provided in Table A1.

Location of research

Research on wheat evolutionary populations (EPs) and wheat landraces has been conducted across a diverse range of agroecological settings, reflecting widespread interest in enhancing crop adaptability and resilience.

Wheat evolutionary populations and composite cross populations were studied in eight articles, carried out in Germany, at the Organic Experimental Station in Neu-Eichenberg, Hesse (Baresel et al., 2022; Brumlop et al., 2017); Italy, across multiple farms in Tuscany and Umbria (Bocci et al., 2020) and in terraced fields of Antrona Schieranco, Antrona Valley, Piedmont (Colombo et al., 2022); the United Kingdom, at Wakelyns Agroforestry in Suffolk and other organic farms in Eastern England (Döring et al., 2015; Weedon et al., 2023; Weedon and Finckh, 2019); and the United States, specifically at Montana State University in Bozeman and Washington State University in Pullman (Merrick et al., 2020).

Wheat landraces were the focus of five studies, conducted in Israel, with laboratory research at the Volcani Center (Bet Dagan) and field trials near the Gilat Research Center in the Negev (Abu-Zaitoun et al., 2018); Spain, in the Catalonia region (Carranza-Gallego et al., 2019); Serbia, at the Institute of Field and Vegetable Crops in Novi Sad (Dodig et al., 2012); Italy, in Santa Maria a Monte (Pisa) and Arezzo, Tuscany (Migliorini et al., 2016); and Iran, in the highland rainfed areas of Kurdistan Province (Mohammadi et al., 2015).

Notably, Italy is the only country where both evolutionary populations and landraces were studied, highlighting its significant role in participatory plant breeding and varietal conservation.

Table 1 summarizes articles included in this systematic review on wheat landraces, CCPs, and EPs, across various geographic locations and research scopes. The studies include laboratory and field experiments focusing on genetic diversity, adaptation to environmental stresses, yield stability, and the role of traditional and heterogeneous wheat populations in sustainable agriculture and climate resilience.

Research objectives of selected articles

This systematic review evaluated a set of peer-reviewed articles examining the performance, adaptation, and utility of wheat evolutionary populations (EPs), landraces, and composite cross populations (CCPs) across varied agroecological contexts. The research aims and objectives of these studies were diverse yet unified by a common goal, which is enhancing crop resilience, genetic diversity, and adaptability under changing climatic and agronomic conditions. The research questions and aims of selected studies are presented in a Table A2. Below is a thematic synthesis of the key objectives and research aims found across the selected studies:

1. Genetic Diversity and Local Adaptation of Landraces

Several studies focused on the characterization and evaluation of genetic resources in wheat landraces, emphasizing their value in semi-arid and rainfed conditions:

- Abu-Zaitoun et al. (2018) aimed to unlock allelic and physiological diversity in Middle Eastern durum wheat landraces to understand their adaptation to semi-arid climates and integrate beneficial traits into modern breeding.
- Dodig et al. (2012) and Mohammadi et al. (2015) evaluated landraces for drought and stress tolerance, highlighting their genetic potential for use in breeding programs targeting resilience under abiotic stress.
- Carranza-Gallego et al. (2019) examined the agronomic and ecological benefits of wheat landrace cultivation under Mediterranean conditions, supporting their role in sustainable farming systems.
- Migliorini et al. (2016) explored the agronomic, nutritional, and consumer-oriented traits of landraces under organic farming, aiming to enhance both productivity and product quality.

These objectives underscore the importance of phenotypic diversity and locally adapted genetic resources for improving resilience in modern wheat systems.

2. Performance and Evolution of Evolutionary Populations (EPs)

Many studies on EPs and Composite Cross Populations (CCPs) focused on their adaptive capacity, yield stability, and performance across environments:

- Baresel et al. (2022) and Brumlop et al. (2017) investigated how within-population diversity and evolutionary history influence agronomic traits and performance stability under different input systems.
- Bocci et al. (2020) aimed to test the hypothesis that long-term cultivation of genetically diverse EPs in different locations results in divergent evolution, contributing to site-specific adaptation and local yield optimization.
- Döring et al. (2015) and Merrick et al. (2020) sought to compare CCPs to their parental lines and variety mixtures, focusing on agronomic performance, disease resistance, and adaptation to contrasting precipitation zones.
- Weedon et al. (2023) and Weedon and Finckh (2019) examined the buffering potential and yield stability of CCPs, with the former emphasizing resilience to climate variability and the latter exploring seed size effects and management history.

Collectively, these studies highlighted the evolutionary breeding approach as a dynamic method to develop crops with greater genetic plasticity and environmental adaptability, especially in organic or low-input systems.

3. Socioeconomic and Agroecological Integration

A subset of articles extended their objectives beyond agronomic traits to address farmers' preferences, heritage preservation, and territorial revitalization:

- Colombo et al. (2022) aimed to reintroduce traditional rye and wheat varieties in marginal mountain areas, linking agronomic evaluation with the revival of local bread-making traditions.

- Bocci et al. (2020) not only focused on the performance of the populations as earlier stated, but it incorporated gender-disaggregated assessments and engaged various stakeholders (farmers, bakers, millers), acknowledging the social dimension of crop evaluation and adoption.

These selected studies recognize the multifunctionality of agricultural biodiversity, connecting genetics to cultural heritage, community involvement, and rural development. The overview of their research objectives affirms the potential of landraces and evolutionary populations to meet future agricultural challenges through ecological intensification, participatory breeding, and site-specific adaptation. Their broad and strategic evaluation sets a foundation for more resilient and inclusive food systems.

Justification of research of included studies

The included studies in this systematic review were examined for their stated justification of research, that is, the rationales behind their research. These were then thematically categorized to understand the driving motivations behind investigations into evolutionary populations and landraces within the context of climate change and agricultural sustainability. These justifications were grouped into four overarching categories.

(i) Improvement of Agronomic Traits: Four studies (4/13) justified their investigations on the basis of enhancing key agronomic parameters such as yield stability, grain quality, and overall performance across diverse management systems. Brumlop et al. (2017) evaluated the morphological and agronomic performance of three winter wheat composite cross populations (CCPs) maintained under organic vs. conventional regimes, demonstrating the potential of CCPs to sustain yield under differing inputs. Döring et al. (2015) conducted a comparative analysis of CCPs, variety mixtures, and pure lines, finding that heterogeneous populations frequently matched or exceeded the performance of pure lines in both organic and conventional systems. Migliorini et al. (2016) assessed old, modern, and mixed wheat varieties alongside landraces in northern Italy, highlighting how traditional genotypes can offer competitive quality characteristics for organic bread chains. Colombo et al. (2022) reintroduced rye and wheat landraces in the Antrona Valley, linking agronomic suitability with local breadmaking quality and cultural value in marginal areas.

(ii) Pest and Disease Resistance: Four studies (4/13) focused on the innate biotic resilience of genetically diverse populations under pathogen and pest pressure. Baresel et al. (2022) examined the evolutionary adaptation of heterogeneous wheat populations in response to disease challenges, illustrating that diversity within CCPs can confer greater stability under epidemic outbreaks. Weedon and Finckh (2019) explored how genetic background and management regime influence yield stability of heterogeneous winter wheat populations, underscoring the role of diversity in mitigating disease-related yield losses. Extending this theme, Weedon et al. (2023) quantified the buffering potential of CCPs when exposed to rapidly changing environmental conditions, including increased pathogen risks. Mohammadi et al. (2015) evaluated durum wheat landraces under prevailing abiotic and biotic stresses in the highland rainfed regions of Iran, confirming that landrace diversity can enhance resistance to both climatic extremes and endemic diseases.

(iii) Adaptation and Climate Change Mitigation: A predominant justification among the included studies is the investigation of landraces, CCPs and EPs as tools for climate change adaptation and risk mitigation. Four studies (4/13) share this justification. Bocci et al. (2020) assessed yield, yield stability, and farmer preferences of evolutionary bread wheat populations, framing their work as a dynamic solution to climate change. Merrick et al. (2020) demonstrated that evolutionary plant breeding increases stability and adaptation of winter wheat across diverse precipitation zones, spotlighting the role of genetic heterogeneity in buffering against drought and waterlogging. Abu-Zaitoun et al. (2018) unlocked the genetic diversity of a Middle-East panel of durum wheat landraces, aiming to identify genotypes suited to semi-arid climates. Dodig et al. (2012) compared responses to drought stress among 100 wheat accessions and landraces, thereby identifying promising sources of drought resistance for breeding programs targeted at future climate scenarios.

(iv) Advancement of Breeding Techniques: a subset of studies advanced methodological innovations by leveraging genetic diversity and participatory approaches in breeding. Amongst the 13 articles, only one addressed the role of landraces in sustainable Mediterranean agroecosystems, advocating for participatory selection processes that integrate farmer knowledge with scientific breeding to develop varieties better suited to local conditions and climate challenges (Carranza-Gallego et al., 2019). This work underscores the value of decentralized, diversity-based breeding strategies in enhancing both adoption and resilience.

Research findings of the included studies

This systematic review integrates findings from 13 studies on landraces, composite cross populations (CCPs), and evolutionary populations (EPs), highlighting the critical role of genetic diversity in enhancing wheat resilience to environmental stresses, particularly in the context of climate change and underscoring their potential in breeding programs aimed at improving wheat adaptability, yield stability, and overall sustainability in the context of climate change.

Genetic diversity and resilience

A consistent theme across the studies is the value of genetic diversity, particularly in landraces and CCPs, in improving wheat's capacity to withstand environmental stressors. As noted by Abu-Zaitoun et al. (2018), the genetic narrowing of wheat during domestication has limited its adaptability to changing climates. However, landraces, due to their broader phenotypic responses, demonstrate a higher adaptability to stress, particularly in rain-fed environments, making them valuable for climate-resilient breeding programs. Carranza-Gallego et al. (2019) further reinforced the role of landraces in improving agroecosystem sustainability, especially in Mediterranean environments, where conditions are harsh, and soil fertility is low. These studies collectively underscore that integrating landraces into breeding programs can help enhance resilience to environmental fluctuations without compromising yield.

Harnessing CCPs for yield stability and climate adaptation

The potential of CCPs, as highlighted by Baresel et al. (2022), is particularly notable in organic farming systems, where they not only yielded comparably to commercial varieties but also exhibited higher stability and disease resistance due to their genetic diversity. Similarly, the study by Bocci et al. (2020) demonstrated that evolutionary populations, selected through natural selection and farmer input, achieved high yields and stability, often exceeding commercial varieties under organic farming conditions. The adaptability of these populations to varying environmental conditions, driven by natural selection, provides a compelling case for their inclusion in breeding strategies aimed at addressing climate change challenges.

Brumlop et al. (2017) found that CCPs' performance was strongly influenced by the genetic background of their parental varieties, with high-yielding CCPs outperforming others in yield, except under extreme winter stress. These findings suggest that parental selection is crucial in establishing CCPs, particularly for traits such as winter hardiness and quality that may not be directly influenced by natural selection. Moreover, the results from Weedon and Finckh (2019) and Weedon et al. (2023) highlighted the long-term yield stability of CCPs in both organic and conventional systems, showcasing their potential for broad adaptability across diverse environments.

Regional adaptation and marginal environments

The studies on marginal environments, such as the Antrona Valley and Mediterranean regions, reveal the significance of selecting crops specifically adapted to challenging conditions. Colombo et al. (2022) demonstrated that certain landraces and evolutionary populations, such as the San Pastore and Solibam varieties, showed remarkable yield stability in mountainous regions, where modern hybrids often failed. Similarly, Dodig et al. (2012) found that landraces from the Western Balkans exhibited better drought tolerance, despite lower average yields, highlighting their potential for breeding drought-resistant wheat varieties in water-limited environments.

The findings of Mohammadi et al. (2015) further confirm the utility of landraces for improving stress resistance, particularly under cold and drought conditions. Landraces from Asia and Europe demonstrated superior genetic potential for both yield and cold tolerance, making them valuable genetic resources for durum wheat breeding in cold-prone regions.

Nutritional and market benefits

In addition to agronomic benefits, studies such as those by Migliorini et al. (2016) highlight the nutritional advantages of wheat landraces and older varieties, which have higher concentrations of essential micronutrients and antioxidants compared to modern cultivars. This presents not only an opportunity to address micronutrient malnutrition but also opens new market opportunities for traditional wheat products with health-beneficial properties. The preference for bread made from older varieties suggests that consumer demand could drive the adoption of these varieties in certain regions, particularly where nutritional quality is a key consideration.

Implications for breeding programs

The collective findings from these studies have significant implications for future wheat breeding programs. First, the incorporation of landraces and CCPs into breeding strategies offers a means to enhance genetic diversity, which in turn can improve yield stability, disease resistance, and adaptability to environmental stresses. As demonstrated by Merrick et al. (2020), the superior adaptability and performance of evolutionary populations in diverse environments underline the importance of utilizing naturally selected populations for long-term sustainability.

Furthermore, the ability of landraces and CCPs to maintain competitive yields under organic and low-input farming systems provides an alternative to modern, genetically uniform varieties that may struggle to cope with increasingly erratic climatic conditions. The focus on decentralized seed production and regional adaptation, as proposed by Weedon et al. (2023), suggests that localized breeding efforts could play a pivotal role in enhancing wheat resilience to future climate challenges.

Comparisons between modern varieties vs. wheat landraces, CCPs, and EPs

Table 2 compares modern varieties of wheat against its landraces, Composite Cross Populations (CCPs), and Evolutionary Populations (EPs), across four key adaptation traits: yield stability, disease resistance, drought tolerance, and nutritional quality. This table synthesizes true measurements from diverse field trials, giving a more grounded comparison of how genetic diversity in Wheat landraces, CCPs, and EPs, translates into improved adaptation traits under climate-related stresses.

Adaptation traits such as yield stability, disease resistance, drought tolerance, and nutritional quality of modern varieties of wheat and Wheat landraces, CCPs and EPs, were compared, although these values were drawn from different experimental settings and methodologies, they indicate a trend toward greater yield stability in genetically diverse populations such as landraces, CCPs and EPs. Included studies show that modern varieties exhibit a yield-stability coefficient of variation (CV) of up to 14.9 %, while evolutionary populations (EPs) and composite cross populations (CCPs) show lower CVs of 10.5 % and 11.6 %, respectively, according to Merrick et al. (2020) and Brumlop et al. (2017). Landraces fall in between, yet lower than the modern varieties, averaging a CV of 12.8 % (Migliorini et al., 2016). Regarding stripe-rust resistance, modern checks record an area under the disease progress curve (AUDPC) of approximately 220, compared to ∼185 in EPs, ∼160 in landraces, and ∼150 in CCPs (Baresel et al., 2022), suggesting enhanced disease suppression in populations with greater genetic heterogeneity. Under drought conditions, yield

TABLE 2 Modern varieties of wheat vs. wheat EPs, CCPs, and landraces: adaptation traits.

Adaptation trait	Modern varieties	EPs	Landraces	CCPs
Yield stability (CV*)	CV ≤ 14.9 %	CV ≤ 10.5 %	CV ≈ 12.8 %	CV ≤ 11.6 %
Disease resistance-stripe rust (AUDPC**)	≈ 220	≈ 185	≈ 160	≈ 150
Drought tolerance (relative yield under stress***)	∼ 75 %	∼ 85 %	∼ 90 %	∼ 88 %
Nutritional quality (grain protein %****)	12.0 %	13.0 %	14.0 %	10.1–10.7 %

*CV, coefficient of variation of yield across environments (lower = more stable).
**AUDPC, area under the disease progress curve for stripe rust (lower = more resistant).
***Relative yield: yield under drought (or stress) expressed as a percentage of the non-stress control.
****Grain protein %: crude protein content measured in harvested grain.

retention relative to optimal conditions is about 75 % in modern cultivars, while EPs maintain ∼85 %, landraces ∼90 % (Dodig et al., 2012), and CCPs ∼88 % (Brumlop et al., 2017), underscoring superior drought resilience in landraces, CCPs and EPs. Finally, average grain-protein content is reported at 12.0 % in modern varieties, 13.0 % in EPs (Bocci et al., 2020), 14.0 % in landraces, and between 10.1–10.7 % in CCPs (Brumlop et al., 2017), reflecting a potential trade-off between protein enrichment and broader agronomic adaptation.

Discussion

The collective evidence from the reviewed studies highlights the fundamental importance of genetic diversity in enhancing wheat's adaptability and resilience to the complex and multifaceted challenges posed by climate change. Modern wheat varieties, heavily shaped by domestication and conventional breeding, exhibit a significant narrowing of genetic diversity, which has compromised their ability to cope with environmental stresses. This reduction underscores the need to revisit and incorporate more genetically diverse resources, such as landraces, Composite Cross Populations (CCPs), and Evolutionary Populations (EPs), into breeding strategies aimed at climate adaptation.

Wheat landraces emerge as a particularly valuable genetic reservoir due to their broad phenotypic variation and inherent adaptability, especially in Mediterranean and other stress-prone regions characterized by water scarcity and climatic extremes. The studies reviewed, including those by Bocci et al. (2020) and Abu-Zaitoun et al. (2018), support the notion that these landraces embody genetic traits that have been naturally selected to withstand environmental variability. This evidence suggests that integrating landrace germplasm into local breeding programs can substantially improve wheat resilience, thereby enhancing crop performance in areas vulnerable to drought and heat stress.

In parallel, CCPs offer a dynamic genetic resource that exhibits notable yield stability and biotic stress resistance under organic and low-input farming conditions. The adaptability of CCPs, as highlighted in research by Brumlop et al. (2017) and Weedon and Finckh (2019), reflects the advantage of maintaining genetic heterogeneity in the face of evolving pest and disease pressures. Moreover, the natural selection processes shaping CCPs lead to morphological and phenological traits that confer environmental plasticity, a crucial factor in sustaining yield under diverse and fluctuating climatic scenarios. These characteristics position CCPs as a promising tool not only for agronomic performance but also for promoting sustainable farming systems.

Evolutionary Plant Breeding (EPB) techniques extend this concept by deliberately fostering evolving wheat populations that adapt continuously to local conditions through natural selection. The improved grain yield, protein content, and disease resistance observed in EP populations (Merrick et al., 2020; Baresel et al., 2022) reinforce the value of EPB in developing resilient cultivars that maintain performance stability amid environmental variability. This dynamic breeding approach aligns well with the unpredictability of climate change, offering a practical means to sustain wheat productivity over time.

Importantly, the reviewed literature also underscores the necessity of tailoring wheat breeding to specific environmental contexts, particularly in challenging Mediterranean and mountainous landscapes. As shown by Carranza-Gallego et al. (2019), wheat populations that leverage genetic variability exhibit superior stress tolerance and yield stability under water-limited conditions. This finding points to the critical role of environment-specific breeding programs that capitalize on local adaptation to confront climate-related stresses effectively.

Despite these promising insights, notable gaps persist in the current research landscape. Most studies focus on limited geographic and environmental contexts, and there remains a paucity of long-term, large-scale field trials to confirm the durability of adaptive traits across variable climates. Additionally, there is insufficient integration of advanced genomic tools with traditional breeding methods to accelerate the identification and utilization of adaptive traits. Socio-economic dimensions, including farmer adoption rates and market viability of genetically diverse populations, also warrant greater attention to ensure practical implementation.

Looking forward, future research should prioritize multi-environmental testing and genomic characterization of landraces, CCPs, and EPs to deepen understanding of their adaptive mechanisms. Participatory breeding approaches that engage local farming communities could enhance the relevance and adoption of these genetic resources. Furthermore, exploring the intersection of genetic diversity and agronomic management will be essential to optimize resilience and sustainability in wheat production systems confronted by climate change.

In conclusion, the reviewed studies collectively affirm that incorporating genetic diversity from wheat landraces, CCPs, and EPs is a vital strategy for enhancing crop resilience to climate change. These genetic resources offer a pathway toward more stable yields, improved stress tolerance, and sustainable agricultural systems, particularly in vulnerable regions. Embracing this diversity in future breeding programs not only supports food security but also promotes adaptive capacity in the face of evolving environmental challenges.

Research gaps and recommendations

Despite the promising findings regarding the use of Evolutionary Populations (EPs), landraces, and Composite Cross Populations (CCPs) for enhancing wheat resilience and climate adaptability, several critical gaps persist in the current body of research. These gaps limit the effective deployment and mainstream integration of EPs into agricultural systems, particularly in diverse global contexts. This section outlines the major gaps identified in the systematic review and proposes targeted recommendations to address them, along with their implications for practice and future research directions.

Geographical limitations and lack of global applicability

One of the most prominent gaps identified in this review is the geographic concentration of studies. The majority of research on EPs and CCPs has been conducted in Europe, particularly in countries such as Italy, Germany, and the United Kingdom. While this provides valuable insights within temperate and organic systems, it restricts the generalizability of findings to broader agroecological zones. To address this, future studies must expand to include underrepresented regions, such as Sub-Saharan Africa, South Asia, and Latin America. Conducting research in these regions will help validate the performance of EPs under different stress environments and socio-economic contexts, enhancing their global relevance and adoption potential.

Limited understanding of farmer perception and adoption

Another critical gap is the limited investigation into farmer awareness, perception, and adoption of EPs and landraces. Despite the participatory nature of evolutionary breeding, few studies directly assess how farmers view these populations, what factors influence their decision to adopt or reject them, and what barriers they face in doing so. Future research should prioritize qualitative and quantitative studies on farmer decision-making, using participatory rural appraisals, behavioral models, and socioeconomic analyses. A deeper understanding of farmers' perspectives will inform more effective outreach strategies and policy interventions aimed at scaling up the use of EPs.

Post-harvest performance and processing challenges

While agronomic and yield-related traits of EPs are frequently studied, there is a lack of attention to post-harvest qualities such as grain uniformity, milling efficiency, and end-use suitability, particularly in baking and flour processing. The inherent variability of EPs poses challenges to standardization and commercialization, often misaligning with industrial expectations. Future studies should evaluate the physicochemical properties of EP-derived grains, their performance in different food processing scenarios, and consumer acceptability of resulting products. Addressing this gap is critical to bridging the divide between field performance and market potential.

Need for long-term and multi-location trials

Many existing studies are based on short-term trials or limited environmental conditions, which do not fully capture the long-term evolutionary potential and stability of EPs. There is a need for more robust, multi-year and multi-location field trials comparing EPs, CCPs, and commercial varieties under both conventional and organic systems. Such studies would strengthen empirical evidence and better inform breeding programs, farmers, and policymakers about the reliability and scalability of these populations across time and space.

Underexplored socio-economic and institutional dimensions

The integration of EPs into agricultural systems requires more than agronomic validation-it demands an understanding of the socio-economic and institutional factors that shape adoption, dissemination, and sustainability. Aspects such as market access, seed regulation, gender roles, and institutional support mechanisms remain largely unexplored. Future research should incorporate socio-economic studies to investigate how these dynamics influence the uptake of EPs and how supportive infrastructure, and policy frameworks can be designed to enhance their use.

Fragmentation in interdisciplinary approaches

Finally, the current literature reflects a degree of fragmentation across disciplines. Agronomic and breeding studies often proceed without integration of socio-economic, food science, or policy perspectives. To harness the full potential of EPs, there is a pressing need for transdisciplinary research that bridges these divides. Collaborative efforts involving plant scientists, economists, extension agents, food technologists, and social scientists will yield a more holistic understanding and facilitate the broader implementation of EPs in diverse farming systems.

Implications for practice

For breeding programs, the findings of this review support the integration of EPs and CCPs into formal selection pipelines, especially climate-resilient and organic systems. Extension services and non-governmental organizations should promote participatory breeding models and educate farmers about the potential of EPs. Policymakers must also adapt seed regulations and subsidy frameworks to recognize and support the unique characteristics of EPs. In the food industry, tailored processing technologies and marketing strategies should be developed to accommodate the variability of EP-derived products.

Future research directions

Moving forward, research should focus on expanding the geographic scope of EP trials, especially in low- and middle-income countries. There is also a need to explore gender dynamics and equity in access to EPs, study the nutritional qualities of EP-derived grains, and assess the feasibility of decentralized seed systems. Innovations in food processing that tolerate compositional variability are equally important for linking EP production with end-use viability. Furthermore, creating inclusive value chains and market channels for EP products will be crucial for their long-term success.

Contribution to existing knowledge

This systematic review advances the current understanding of evolutionary populations (EPs) and landraces in wheat breeding by updating and expanding upon earlier foundational works such as Döring et al. (2011) and Ceccarelli and Grando (2020). While those reviews laid the conceptual groundwork for evolutionary plant breeding and its relevance to climate resilience, the present study integrates a broader and more recent body of empirical evidence (2012–2023) using a structured and replicable PRISMA-based approach.

Unlike previous narrative syntheses, this review employs quantitative comparative metrics, such as yield stability coefficients, disease resistance indices, drought tolerance ratios, and grain protein content, to evaluate the adaptive performance of EPs, CCPs, and landraces relative to modern varieties. Additionally, the review highlights underexplored dimensions, including post-harvest performance, adoption barriers, and regional research gaps, particularly in low- and middle-income countries.

By systematically identifying these knowledge gaps and synthesizing data across agroecological contexts and breeding strategies, this review provides a timely and evidence-based framework to guide future research, breeding programs, and policy development for climate-resilient wheat systems.

Conclusion

This systematic review, encompassing 13 studies, underscores the vital role that genetic diversity-through Evolutionary Populations (EPs), landraces, and Cross Composite Populations (CCPs), can play in addressing the multifaceted challenges posed by climate change, population growth, and food security. The integration of genetically diverse populations, such as landraces, composite cross populations (CCPs), and evolutionary populations (EPs), into wheat breeding represents not only a strategic innovation but an ecological necessity in the face of climate change. These populations offer proven resilience to environmental stressors, superior performance in marginal areas, and enhanced nutritional profiles, positioning them as valuable assets in the pursuit of sustainable and food-secure agriculture.

However, these advantages raise a crucial question: to what extent are such genetically diverse grains compatible with the demands of the agro-industrial and food processing sectors, which are often built around the predictability and standardization offered by modern, uniform varieties? While genetic diversity ensures adaptability and food quality at the farm level, it may pose challenges for large-scale processing chains that rely on homogeneous raw materials for efficiency, consistency, and product formulation.

This tension highlights the need for further interdisciplinary inquiry, not only agronomic, but also economic, technological, and regulatory, to reconcile the goals of agro-biodiversity and resilience with the structural requirements of the global food system. Institutional support, market innovation, and adaptive processing technologies will be key to unlocking the full potential of these populations, ensuring that diversity in the field can translate into viable and scalable models of production, distribution, and consumption.

Nevertheless, gaps remain in understanding farmers' awareness and adoption of EPs, particularly in terms of how these populations can be effectively integrated into existing agricultural practices. Future research efforts should address these gaps and expand globally, targeting key staple crops like rice, maize, and millet to further enhance global food security through the adaptive potential of EPs.

Finally, while these populations demonstrate strong adaptability to climate change and maintain stable yields and organoleptic qualities, challenges remain in the processing of flours derived from these populations. The varying yield qualities of EPs, influenced by cultivation conditions, may not align with the predominant value chains in wheat flour production. This misalignment underscores the necessity of innovative food processing methods and a tailored marketing strategy to incorporate EP-derived flours into existing systems.

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

KB: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Resources, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. NM: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Resources, Software, Supervision, Visualization, Writing – original draft, Writing – review & editing. MG: Validation, Writing – original draft, Writing – review & editing. SC: Investigation, Supervision, Validation, Writing – review & editing. SF: Writing – review & editing. GG: Funding acquisition, Project administration, Resources, Supervision, Validation, Writing – review & editing.

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Conflict of interest

SF was employed by Open Fields Srl.

The remaining 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.

Generative AI statement

The author(s) declare that no Gen AI was used in the creation of this manuscript.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2025.1504922/full#supplementary-material

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