AGRICULTURAL SCIENCE AND TECHNOLOGY, VOL. 17, No 2, pp 3-22, 2025
Published by Faculty of Agriculture, Trakia University, Bulgaria
ISSN 1313-8820 (print)
ISSN 1314-412X (online)
http://www.agriscitech.eu
DOI: 10.15547/ast.2025.02.015

Review

Sustainable wheat cultivation in Asia: insights and innovations from long-term field experiments

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(Manuscript received 05 May 2025; accepted for publication 09 June 2025)

Abstract. *Wheat plays a critical role in ensuring food security across Asia, where increasing demand, resource limitations, and climate change pose significant challenges to the sustainability of production. Long-term field experiments (LTEs), characterized by decades of continuous observation, provide essential evidence regarding the impacts of agronomic practices on productivity, soil health, climate resilience, and resource efficiency. This review synthesizes findings from LTEs conducted in Asia and worldwide to evaluate the sustainability of wheat-based systems. Yield trends observed in Long-term field experiments highlight the advantages of crop rotation, conservation practices, and integrated nutrient management in stabilizing productivity. Although continuous wheat cultivation can lead to soil degradation, practices such as organic amendments and optimized nitrogen management have been shown to enhance soil fertility and nutrient use efficiency. Water management, particularly in water-scarce regions, remains a critical concern; strategies such as mulching, root architecture optimization, and the balance of nitrogen and phosphorus offer measurable improvements in water use efficiency. Additionally, Long-term field experiments illuminate potential pathways for mitigating greenhouse gas emissions through reduced reliance on synthetic inputs and the adoption of conservation agriculture techniques. Despite these advancements, significant knowledge gaps persist concerning the socio-economic scalability of these practices, interactions among genotype, environment, and management, and the effectiveness of institutional support systems. This review identifies priorities for future LTEs, emphasizing the need for multidisciplinary approaches, long-term climate risk monitoring, and innovations in data management. Furthermore, policy support is crucial for institutionalizing LTE networks, enhancing farmer engagement, and mainstreaming sustainable wheat cultivation. The findings underscore the indispensable role of Long-term field experiments in developing resilient wheat systems that align with food security and environmental objectives in Asia.*

Keywords: long-term field experiments, sustainable wheat cultivation, soil health and nutrient dynamics, climate resilience, agricultural policy in Asia.

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Introduction

Wheat plays a pivotal role in ensuring food security across Asia, having undergone substantial increases in both production and cultivated area over recent decades (Kumari et al., 2022). However, several emerging challenges — such as rapid population growth, climate variability, and stagnating productivity within rice–wheat systems — pose significant risks to future food supplies in the region (Hobbs and Morris, 1996; Kumari et al., 2022). The decline in productivity is attributed to multiple factors, including soil degradation, water scarcity, heightened pest and disease pressures, and delays in planting (Hobbs and Morris, 1996; Grote et al., 2021). Addressing these complex challenges requires a coordinated effort to implement improved crop management strategies, enhance access to high-quality seeds and inputs, and increase support for resource-constrained farmers (Grote et al., 2021). Furthermore, it is imperative to realign research priorities to emphasize sustainability, climate change adaptation, and the promotion of healthier diets — factors that are crucial for achieving long-term food security (Grote et al., 2021; Byerlee, 1992). This is particularly pertinent in the Asian context, where recent long-term experiments (LTEs) conducted in countries such as India and China have yielded valuable insights into sustainable wheat production amid changing climatic conditions (Ladha et al., 2020; Zhang et al., 2019). The incorporation of such region-specific evidence not only enhances contextual relevance but also informs targeted policy and agronomic interventions. Such efforts are vital for preserving the productivity potential and ecological stability of irrigated cropping systems in South Asia (Byerlee, 1992). Long-term experiments (LTEs) provide invaluable insights into the dynamics of sustainable agricultural systems, particularly concerning soil fertility and crop productivity (Poulton, 1995). The Rothamsted experiments, among the oldest continuously running agricultural trials globally, have demonstrated the lasting benefits of fertilizers, crop rotation, and systematic management practices in sustaining yields and preserving soil health over extended periods (Johnston and Poulton, 2018; Macdonald et al., 2020). These experiments also serve as crucial platforms for monitoring environmental trends, evaluating agricultural management practices, and understanding biodiversity responses (Macdonald et al., 2020). Similarly, the Magruder Plots, established in 1892 for continuous winter wheat cultivation, have contributed significantly to advancing knowledge of yield responses to soil amendments, nutrient cycling, and organic matter dynamics (Girma et al., 2007). Unlike short-term studies, LTEs reveal long-term ecological and agronomic interactions, allowing for the re-examination of historical data and archived samples to address emerging research questions (Poulton, 1995; Macdonald et al., 2020). The future of wheat cultivation in Asia is increasingly uncertain due to the impacts of climate change. In South Asia alone, more than 400 million metric tons of wheat will be required by 2050 to meet projected demand (Sukumaran et al., 2021). The emergence of wheat blast in Bangladesh and eastern India has further amplified concerns, highlighting the urgency of implementing robust detection, surveillance, and mitigation strategies (Yesmin et al., 2020). While wheat has traditionally been of limited importance in Southeast Asia, changing climatic and socio-economic conditions have spurred growing interest in its regional potential (Aggarwal, 1988). To address these challenges, research efforts are focusing on developing climate-resilient wheat cultivars through advanced pre-breeding techniques, including the screening of diverse germplasm, targeted hybridization, and high-throughput phenotyping (Sukumaran et al., 2021). Furthermore, initiatives aim to improve grain quality for specific end-uses, such as bioenergy and nutrition, while reducing dependence on agrochemical inputs (Grewal and Goel, 2015). Achieving these objectives requires collaborative, interdisciplinary research frameworks to ensure the continued productivity of wheat under changing climatic conditions across Asia.

Material and Methods

This review synthesizes research findings from long-term wheat experiments (LTEs) conducted in Asia and other global regions to assess the sustainability of wheat-based cropping systems. A structured literature review and meta-synthesis approach was used, focusing on studies lasting at least 10 years, especially those longer than 20 years, as these meet the widely accepted definition of long-term experiments in agricultural research. Primary sources comprised peer-reviewed journal articles, institutional reports, and data from reputable experimental sites, including the Magruder Plots at Oklahoma State University in the United States (established in 1892), the Rothamsted Experiment in the United Kingdom, the Moreau Field in Japan, as well as long-term experiments conducted in India, China, and the Gangetic Plain in South Asia. Relevant studies were searched using academic databases including Scopus, Web of Science, and Google Scholar, using a combination of keywords such as “long-term wheat experiment”, “soil health”, “climate resilience”, “nutrient management”, “greenhouse gas emissions” and “Asia”. Selected studies were rigorously screened and evaluated based on the rigor of experimental design, duration, data consistency, and relevance to sustainability indicators such as crop yield trends, soil fertility parameters, water use efficiency, and greenhouse gas emissions. In addition, we included comparative analyses of conventional management and conservation management practices under different agro-ecological conditions. Quantitative data are extracted where available and synthesized qualitatively to identify recurring patterns, trade-offs, and context-specific outcomes. Emphasis is placed on cross-national comparisons, integrated management frameworks, and interactions between environmental, agronomic, and socioeconomic variables. Modeling studies, meta-analyses, and statistical methods such as longitudinal analysis and smoothing are cited where appropriate to interpret long-term trends and variability.

Long-Term Wheat Experiments in Asia

Long-term field experiments (LTFEs) in agriculture, typically defined as studies that span at least 20 years, offer valuable insights into sustainable soil management and crop productivity (Grosse et al., 2020). A comprehensive review of long-term field experiments (LTFEs) identified 205 studies conducted in Germany and 186 studies conducted in other European countries. These experiments primarily focused on investigating the effects of fertilization, tillage practices, and crop rotation on agricultural systems (Grosse et al., 2020; Grosse et al., 2021). In Russia, a network of LTFEs was established during the 1920s and 1930s, and currently includes 130 active experiments (Romanenkov et al., 2020). The Rothamsted Research Station in the United Kingdom hosts some of the oldest and most renowned LTFEs, including the Broadbalk Wheat and Hoosfield Spring Barley experiments. These studies have provided significant insights into fertilizer usage, crop rotation, and soil management since their inception in the mid-19th century (Macdonald et al., 2020). These long-term experiments remain invaluable for studying agricultural sustainability, biodiversity, and the effects of climate change on crop-soil systems.

Long-term wheat experiments have been pivotal in advancing our understanding of sustainable crop production and ecosystem health since the late 19th century. Noteworthy examples include the Magruder Plots, which were established in 1892 (Girma et al., 2007), and the Rothamsted Experiments, initiated nearly 150 years ago (Jenkinson, 1991). These experiments have provided crucial insights into soil fertility, organic matter dynamics, and crop yield patterns over extended periods. The Magruder Plots have demonstrated the viability of continuous wheat production without fertilization for over a century (Girma et al., 2007). Similarly, the Rothamsted Experiments have shown that annual fertilization in wheat and barley monocultures can sustain and even enhance grain yields (Jenkinson, 1991). Long-term experiments provide unique opportunities to study agricultural system transformations, develop accurate models, and evaluate sustainability (Hmielowski, 2017). Despite the challenges associated with maintaining such studies, they remain indispensable for understanding long-term agricultural processes and informing future farming practices (Jenkinson, 1991; Hmielowski, 2017).

Long-term agricultural experiments are essential for understanding the effects of farming practices on crop yields and soil fertility over extended timescales (Caldrone et al., 2024). These studies face significant challenges in their design, analysis, and reporting, requiring meticulous planning and the use of statistical methods to account for both spatial and temporal variability (Orchard et al., 2000; Lark et al., 2020). For example, the Morrow Plots in the United States, established in 1876, investigate the impact of crop rotation and fertility treatments on maize yields (Caldrone et al., 2024), while a conservation agriculture trial in Malawi, initiated in 2007, explores resilient cropping systems (Lark et al., 2020). Advanced statistical techniques, such as cubic smoothing spline methods and longitudinal analysis, are employed to analyze the dataset complexes generated by these experiments (Orchard et al., 2000; Lark et al., 2000; Lark et al., 2020). Furthermore, functional mapping approaches can be utilized to monitor the spatio-temporal dynamics of agronomic traits in crop genetic studies, as demonstrated in a wheat MAGIC population (Camargo et al., 2018).

Productivity Trends and Yield Stability of Long-Term Wheat Experiments

Long-term wheat experiments offer significant insights into yield stability and productivity trends. Research indicates that factors such as crop rotation and nitrogen fertilization play pivotal roles in influencing the stability of wheat yields. Specifically, the implementation of rotational cropping systems combined with adequate mineral nitrogen fertilizer usage has been shown to mitigate yield risk and variability (Macholdt et al., 2020). In contrast, continuous wheat monoculture systems tend to exhibit heightened yield risks and greater inter-annual variability (Macholdt et al., 2020). Furthermore, climatic factors such as water deficits during the vegetative growth phase negatively impact average yield; however, water deficits occurring near harvest can result in positive yield effects (Hadasch et al., 2020). Yield stability analyses indicate a gradual increase in yield variance over time for both wheat and rye populations (Hadasch et al., 2020). The yields from check plots in long-term experiments demonstrate considerable variability, with coefficients of variation around 30%, which is comparable to yields from fertilized plots (Fornah et al., 2020). This unpredictable variability underscores the necessity for mid-season adjustments to nitrogen application rates (Fornah et al., 2020). Collectively, these studies underscore the critical role of agronomic management practices in sustaining wheat yield stability amid evolving environmental conditions (Macholdt and Honermeier, 2018).

Long-Term Yield Trends Under Different Management Systems: Long-term agricultural experiments are essential for comprehensively understanding the impacts of farming practices on crop yields and sustainability over extended periods (Caldrone et al., 2024; Orchard et al., 2000). However, these studies face challenges related to experimental design and statistical analysis, necessitating meticulous planning and management of data (Orchard et al., 2000; Lark et al., 2020). Evidence suggests that innovative cropping systems, including low-input and conservation agriculture, can diminish reliance on synthetic pesticides without adversely affecting yields (Bellone et al., 2023). Nonetheless, the effects of various treatments may differ across seasons and interact with climatic conditions, highlighting the importance of conducting longitudinal analyses (Lark et al., 2020). To ensure sufficient statistical power, future trials should prioritize increasing replication and judiciously selecting treatments (Lark et al., 2020). The long-term datasets generated from these experiments serve as valuable resources for validating previous findings and facilitating new analyses, thereby contributing to the advancement of sustainable agricultural practices (Caldrone et al., 2024).

Intensification, diversification and system sustainability: Long-term agricultural experiments reveal strategies for sustainable intensification and diversification of crop systems. Incorporating hybrid rice, potato, and pulses into rice-wheat rotations can increase productivity, profitability, and energy efficiency while improving soil fertility (Kumar et al., 2001). Long-term trends reveal a divergence in yield performance within rice-wheat systems; specifically, rice yields have been observed to decline in certain regions due to factors such as soil degradation, water scarcity, and diminishing input efficiency. In contrast, wheat yields have exhibited a gradual increase, potentially attributable to the adoption of improved varieties and enhanced agronomic practices (Timsina et al., 1997). The Long-term Agro-Ecosystem Research Network is evaluating sustainable intensification strategies that include reducing input dependence, diversifying management, improving adaptive capacity, and managing multiple ecosystem services (Spiegal et al., 2018). Ecological intensification practices, such as increasing crop diversity and increasing organic matter, can have a positive impact on long-term crop yields, especially under low nitrogen fertilizer applications. These practices can partially replace nitrogen fertilizers at different tillage intensities without significantly affecting yields (MacLaren et al., 2022). These findings highlight the potential of ecological approaches to enhance agricultural sustainability while maintaining productivity.

Trade-offs between yield and input utilization: Long-term studies on wheat production reveal important trade-offs between yield and input use. In the North China Plain of China, yield and efficiency can be improved by optimizing water and nitrogen management, potentially reducing irrigation by 127 mm and nitrogen application by 89 kg/ha, while increasing water use efficiency by 60% and nitrogen use efficiency by 77% (Bai et al., 2020). A 42-year study in Alberta, Canada, found that continuous wheat rotations combined with nitrogen and phosphorus fertilizer applications provided the highest average net returns, although with greater variability compared to fallow-wheat rotations (Smith et al., 2015). In China's wheat-maize rotation system, farmers achieved yields close to 80% of achievable yields, but excessive nitrogen fertilizer application led to inefficiencies. Only 15% of wheat and 4% of maize fields achieved the dual goals of high yield and efficient fertilization, indicating the potential for sustainable intensification through improved fertilizer management techniques (Li et al., 2019).

Soil Health and Nutrient Dynamics

Long-term wheat experiments offer valuable insights into soil health and nutrient dynamics. The Magruder Plots, which were established in 1892, demonstrate that continuous wheat production without fertilization can sustain yields exceeding 1 Mg ha^{−1}, a value clearly articulated in standardized units, despite a substantial decline in soil organic matter (Girma et al., 2007). In Pendleton, Oregon, an 84-year study indicated that the application of farmyard manure significantly increased levels of soil organic carbon, total nitrogen, total sulfur, as well as extractable magnesium, potassium, and phosphorus in the topsoil compared to other treatment modalities (Shiwakoti et al., 2020). A comprehensive 75-year study revealed that disc plowing resulted in higher concentrations of nitrogen in the soil compared to moldboard plowing. Furthermore, higher rates of nitrogen fertilization were correlated with increased levels of phosphorus in the soil (Shiwakoti et al., 2019). However, it is noteworthy that long-term cultivation practices have led to substantial declines in soil phosphorus, organic carbon, magnesium, and calcium when compared to undisturbed pastureland (Shiwakoti et al., 2019). These findings underscore the complex interactions between agricultural management practices and soil nutrient dynamics within long-term wheat production systems.

Impacts of Continuous Wheat Cropping on Soil Physical, Chemical, and Biological Properties: Continuous wheat cropping and rice-wheat rotations exert significant influences on soil properties. Long-term studies conducted over a period of ten years have demonstrated that these practices can result in the formation of a subsurface hardpan, which in turn increases bulk density and reduces hydraulic conductivity (Singh et al., 2009; Rahmati et al., 2011; Balloli et al., 2000). Generally, soil organic carbon and nitrogen levels decline under continuous wheat cropping compared to more diverse rotational systems (Carter, 1984; Singh et al., 2009). Nevertheless, continuous wheat cropping and cereal-grass rotations may enhance the labile organic matter content and nitrogen-supplying capacity in the topsoil when compared to wheat-fallow systems (Carter, 1984). Furthermore, crop rotations that include fallow periods or legumes, such as chickpeas, have demonstrated improvements in soil physical properties, including decreased bulk density, enhanced water aggregate stability, and increased saturated hydraulic conductivity, relative to continuous wheat cropping (Rahmati et al. al., 2011). Additionally, long-term rice-wheat rotations can lead to increases in available phosphorus and micronutrients but may simultaneously deplete available potassium in the soil (Balloli et al., 2000).

Fertilizer Management and Nutrient Use Efficiency: Long-term experiments regarding wheat production have underscored the significant influence of fertilizer management on yield, crop quality, and nutrient use efficiency. The combination of organic manures with chemical fertilizers consistently results in superior outcomes compared to single applications, with wheat yields increasing by up to 15.9% when compared to recommended doses of chemical fertilizers alone (Sheoran et al., 2017). Furthermore, integrating farmyard manure with recommended fertilizer applications has been shown to maximize wheat productivity and enhance various crop quality parameters (Chauhan et al., 2020). Optimal nitrogen application rates vary between 60 and 120 kg/ha, contingent upon specific environmental and agronomic conditions (Pepó, 2002). Fertilizer use efficiency is enhanced through the combined application of organic and inorganic fertilizers, although it is noted that the nutrient harvest index tends to decrease under these conditions (Sheoran et al., 2017). Additionally, long-term fertilization practices influence soil properties; specifically, continuous application of nitrogen alone has been linked to yield declines in acidic soils (Chauhan et al., 2020). In conclusion, adopting appropriate fertilization strategies — particularly those that integrate organic and inorganic sources — is essential for achieving sustainable wheat production, while optimizing yield, quality, and nutrient use efficiency (Lei, 2006; Pepó, 2002).

Organic Matter Dynamics and Carbon Sequestration: Long-term agricultural experiments demonstrate that management practices significantly affect soil organic carbon (SOC) sequestration and crop yields. Transitioning from conventional tillage to no-till farming practices can sequester approximately 57 ± 14 g C m^{-2} yr^{-1}, while enhancing rotation complexity can sequester 20 ± 12 g C m^{-2} yr^{-1} (West end Post, 2002). Nitrogen fertilization has been found to increase SOC levels as well as total nitrogen content, especially at application rates exceeding 90 kg ha^{-1} (Aula et al., 2016). In wheat-fallow systems, the application of manure has been associated with the maintenance of the highest SOC levels and crop yields, whereas other treatments have exhibited declining yields that correlate with reduced soil nitrogen content (Rasmussen and Parton, 1994). The integrated use of farmyard manure with inorganic fertilizers not only improves soil physical properties but also increases SOC pools and enhances crop yields, particularly in maize-wheat rotation systems (Singh et al., 2015). Collectively, these studies emphasize the importance of balanced nutrient management and the application of organic matter inputs in maintaining soil fertility, improving crop productivity, and facilitating carbon sequestration within agricultural systems.

Water resources management and utilization efficiency

Long-term studies on Asian wheat reveal challenges and opportunities for improving water management and water use efficiency. Limited rainfall and high soil evaporation rates in dryland agriculture result in low wheat yield and water use efficiency (WUE) (Qin et al., 2013). Nitrogen fertilizer application can improve yield and WUE, and the optimal application rate depends on soil moisture conditions (Zhong and Shangguan, 2014). However, long-term nitrogen fertilizer application may reduce available soil moisture at planting time, despite its ability to improve yield and WUE (Wang et al., 2012). Irrigation management is critical in semi-arid climates, with seasonal irrigation amounts ranging from 511 to 787 mm and evapotranspiration from 625 to 890 mm (Djaman et al., 2018). Different wheat varieties vary in yield potential and WUE, with TAM107 showing higher yield in one study (Djaman et al., 2018). Strategies such as straw mulching and optimizing sowing date may help improve yield and WUE in water-limited environments (Qin et al., 2013; Djaman et al., 2018). As shown on Figure 1, the water use efficiency (WUE) of TAM107 cultivar under straw mulch was 1.3 kg/m³ and the yield was 5.2 t/ha. This was compared to the other cultivars A and B, which showed slightly lower values. This highlights the importance of breeding for yield and resource use efficiency (Djaman et al., 2018; Qin et al., 2013).

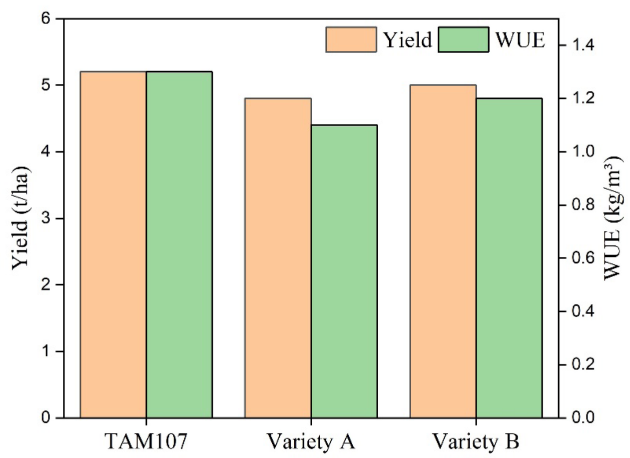

Figure 1. Yield and WUE of Wheat Varieties

Comparison of conventional and alternating wet-dry (AWD) practices: Alternating wetting and drying (AWD) is an irrigation technique for rice cultivation that can effectively reduce water use and greenhouse gas emissions compared to continuous flooding (CF). Several studies have shown that AWD can reduce methane emissions by 2% to 9% without significantly affecting rice yields (Chidthaisong et al., 2018; Tran et al., 2018). In addition, AWD improves water use efficiency, reducing overall water use by 14% to 42% (Chidthaisong et al., 2018; Tran et al., 2017). Although some studies have shown that AWD may lead to an increase in nitrous oxide emissions, its overall global warming potential is still lower than CF (Chidthaisong et al., 2018). However, farmers are often skeptical about adopting AWD due to concerns about water reliability and lack of knowledge (Bwire et al., 2024). To optimize the implementation of AWD, researchers recommend the use of smart sensors, seasonal suitability mapping, and long-term pressure measurements (Bwire et al., 2024). AWD shows promise as a water management strategy to combat climate change, but further research and farmer education are needed to increase its adoption rate (Mote et al., 2017; Bwire et al., 2024). To this end, Table 1 provides a comparative summary of different irrigation practices in terms of water conservation and methane reduction. The sensor-based alternating wetting and drying (AWD) method can save up to 30% of water and reduce methane emissions by 60%, with no significant impact on yield (Chidthaisong et al., 2018; Bwire et al., 2024).

Table 1. Water Use and Emission Reduction under AWD Practices

Practice	Water Saved (%)	Methane Reduction (%)	Yield Impact
AWD with sensors	30	60	No change
AWD without sensors	20	40	Slight reduction
Continuous Flooding	0	0	Baseline

Flooded and Aerobic Systems. Water Productivity: Water productivity (WP) in both flooded and aerobic rice cultivation systems have been the subject of considerable research, revealing that aerobic systems possess significant potential for water conservation. Specifically, aerobic rice cultivation can decrease water consumption by 37% to 45% relative to traditional flooded systems; however, it is important to note that this practice may result in lower yields (Kadiyala et al., 2012).

Additionally, alternating between aerobic and anaerobic conditions or implementing fallow periods can enhance both the yields and WP of aerobic rice (Grassi et al., 2009). In wheat cultivation systems, substituting fallow periods with continuous cropping has been shown to diminish WP, biomass production, and grain yields (Aiken et al., 2013). Moreover, WP exhibits substantial regional variability due to differences in climate and soil conditions, which underscores the necessity of avoiding generalized benchmarks (Edreira et al., 2018).

It is also crucial to recognize that factors unrelated to water availability often impose greater constraints on yield than water supply itself. This insight suggests that there are opportunities to augment food production utilizing existing water resources through enhanced management practices (Edreira et al., 2018).

A thorough understanding of the potential and actual WP on farms operating under water-limited conditions is essential for identifying the elements that influence production capacity in such environments. The WP of wheat varies significantly across different irrigation methods. As depicted on Figure 2, aerobic systems achieve an average WP of 1.2 kg/m³, outperforming traditional flooded systems, which yield only 0.8 kg/m³. Systems that alternate between aerobic and anaerobic conditions provide intermediate benefits, with a WP of 1.0 kg/m³, indicating their potential to optimize both yield and water utilization (Kadiyala et al., 2012; Grassi et al., 2009).

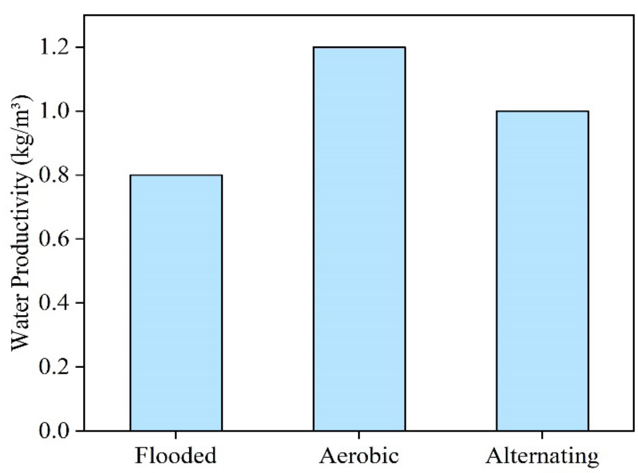

Figure 2. Water Productivity in Wheat Systems

Impacts on water-scarce areas: Long-term experiments on wheat cultivation in water-scarce regions have revealed important insights into improving water use efficiency (WUE) and crop yield. Root architecture plays a key role in drought tolerance, and compact root systems show clear advantages in water-limited environments (Manschadi et al., 2006). However, low water use efficiency remains a challenge, with crops using only one-third of available water for transpiration in some cases (Qin et al., 2013). In particular, nitrogen and phosphorus fertilization can significantly affect water use efficiency and precipitation use efficiency in semi-arid regions (Kröbel et al., 2012). Conservation tillage practices, such as straw mulching and deep tillage, have shown potential for improving soil water storage, photosynthesis, and water use efficiency in wheat and maize (Yang et al., 2021). Long-term application of these practices generally results in higher productivity than short-term applications, highlighting the importance of continuous management strategies in water-scarce regions (Yang et al., 2021).

Greenhouse gas emissions and climate change mitigation

Recent studies have highlighted the complex relationship between agricultural practices, greenhouse gas emissions, and climate change mitigation. Long-term experiments have shown that food production systems can meet both food security and climate stabilization goals by reducing emissions per ton of food output (Liang et al., 2021). In South Asia, rice and wheat production are important sources of greenhouse gas emissions, and livestock also have significant environmental impacts (Sachdeva et al., 2023). Climate change affects carbon allocation in crops, thereby affecting food yields and carbon sequestration potential (Liu et al., 2023). Although farm management practices can enhance soil organic carbon (SOC) sequestration, extreme weather events, especially droughts, may have a greater impact on long-term SOC trends than management interventions (Kabir et al., 2024). These findings highlight the importance of adaptive agricultural strategies needed to balance productivity and environmental sustainability in the context of climate change.

Methane and Nitrous Oxide Emissions from Long-Term Wheat Experiments: Long-term wheat experiments conducted in Asia illustrate the complex interactions between fertilizer management practices and greenhouse gas emissions. Specifically, methane (CH_4) emissions are generally higher in rice-wheat systems, particularly when organic inputs are utilized. Conversely, nitrous oxide (N_2O) emissions tend to increase with the application of mineral fertilizers (Wassmann, 2004). In double-cropping systems, CH_4 emissions peak with high manure application rates, while N_2O emissions rise with the use of mineral fertilizers and the incorporation of rice residues (Tang et al., 2016). The implementation of nitrification inhibitors has been shown to reduce N_2O emissions by as much as 55% in wheat-maize cropping systems (Hu et al., 2013).

Optimized cropping systems have the potential to enhance grain yields while decreasing fertilizer usage and greenhouse gas intensity; however, it is important to note that these systems may not lead to an overall reduction in total emissions or water consumption (Gao et al., 2014). Alternative cropping systems, such as the wheat-maize-spring maize rotation, demonstrate promise in reducing emissions, conserving water, and minimizing fertilizer inputs while still achieving high yields (Gao et al., 2014). Table 2 presents detailed greenhouse gas emission profiles associated with key cropping practices. Additionally, alternate wetting and drying (AWD) and zero-tillage practices have been found to emit lower levels of CH_4 and CO_2 while sustaining competitive yields, thereby highlighting their significance in promoting sustainable wheat production (Tang et al., 2016; Gao et al., 2014; Wassmann, 2004).

Table 2. Greenhouse Gas Emissions by Cropping Practice

Practice	CH_4 Emissions (kg/ha)	N_2O Emissions (kg/ha)	CO_2 Emissions (kg/ha)	Yield (t/ha)
Organic input	120	20	1000	4.5
Mineral input	80	35	1100	5.0
Zero-tillage	70	25	950	4.8
Crop residue	60	18	900	4.6
AWD	30	15	800	4.9

Impacts of water, fertilizer and residue management on greenhouse gases: Long-term studies of wheat systems in Asia have shown that residue and fertilizer management have significant effects on GHG emissions and soil properties. In particular, incorporating crop residues, especially cereal-legume mixtures, into tillage systems can increase yields and reduce GHG emissions from soils (Raseduzzaman et al., 2024). Combinations of organic and inorganic fertilizers generally increase CO_2 and N_2O emissions, but can reduce ammonia losses compared to mineral fertilizers alone (Zhou et al., 2023). Zero-tillage systems can reduce methane emissions but may lead to increased N_2O production compared to conventional tillage (Sapkota et al., 2015). Long-term application of manure consistently yields the highest crop yields and maintains the highest soil carbon and nitrogen content, while other treatments show yield declines as soil nitrogen content decreases (Rasmussen and Parton, 1994). These findings highlight the importance of integrated management practices in balancing crop productivity, soil health, and GHG reductions in wheat-growing systems. Greenhouse gas emissions differ significantly under different nutrition and tillage strategies. As shown in Figure 3, organic fertilizers have the highest methane emissions (70 kg/ha), while mineral fertilizers emit more nitrous oxide (30 kg/ha) but less methane. Zero tillage technology shows a decreasing trend in emissions of all gases, especially in methane and carbon dioxide emissions (Zhou et al., 2023; Sapkota et al., 2015; Raseduzzaman et al., 2024).

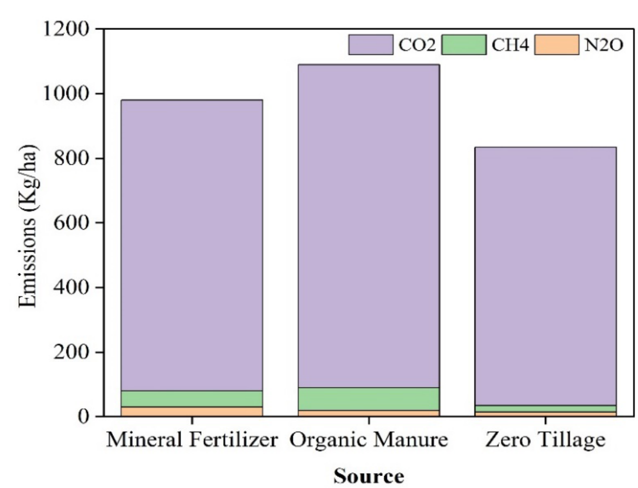

Figure 3. GHG Emissions by Fertilizer and Practice

Potential Mitigation Strategies: Climate change poses a major threat to wheat and maize production, with yields projected to decline by 3% to 34% by 2050 (Hellin et al., 2012). Rust, particularly stem rust strain Ug99, also threatens wheat crops in Asia (Singh et al., 2006). To address these challenges, researchers recommend developing crop varieties with enhanced resistance to heat, drought, and disease (Hellin et al., 2012; R. Singh et al., 2004). Implementing sustainable agronomic practices, such as conservation agriculture and improved nitrogen management, can help mitigate the effects of climate change (Hellin et al., 2012). In terms of rust control, the deployment of disease-resistant varieties based on mild and slow rust genes shows promise (Singh et al., 2004). In rice-wheat rotation systems, resource-saving technologies, such as no-till wheat and direct-seeded non-irrigated rice, can improve sustainability (Nawaz et al., 2019). In addition, policy innovation and infrastructure investment are critical to promote technology adoption and enhance farmers' livelihood security (Hellin et al., 2012). Table 3 lists several climate-resilient wheat strategies, including drought- and disease-resistant lines, and optimized planting practices. These measures can achieve modest yield gains (5%–10%) and vary in implementation timeframes, thereby supporting long-term adaptation to stress (Hellin et al., 2012; Singh et al., 2006).

Table 3. Climate-Resilient Wheat Strategies

Strategy	Target Stress	Expected Yield Impact	Timeframe
Drought-resistant varieties	Drought	+10%	Mid-term
Disease-resistant lines	Pathogens	+8%	Long-term
Optimized planting	Multiple	+5%	Short-term

Climate Resilience and System Adaptability of Long-Term Wheat Experiments

Climate change presents significant challenges to global food security, particularly in cereal production systems. Long-term studies conducted in Asia have demonstrated that climate-resilient technologies can enhance agricultural resilience in rainfed ecosystems (KrishiKosh, 2020). Research in northern India illustrates the potential of integrating remote sensing, deep learning, and crop modeling to identify food security hotspots and predict the impacts of climate change on wheat yields (Willmes et al., 2024). In China's North China Plain, winter wheat-summer maize rotation systems have successfully increased yields while simultaneously reducing greenhouse gas emissions through improved nitrogen management and residue incorporation (Liang et al., 2021). Climate risk assessments for winter wheat in the US Great Plains indicate that aligning crop phenology with periods less susceptible to water deficit and temperature stresses can enhance yield stability (Lollato et al., 2020). Collectively, these studies underscore the critical importance of adaptive strategies and technological innovations in bolstering the climate resilience of wheat production systems across Asia and beyond.

Response of Wheat Systems to Climate Variability and Extremes: Long-term investigations into wheat systems in Asia reveal substantial impacts of climate variability and extremes on productivity. In Punjab, India, increasing minimum temperatures and decreasing sunshine hours have adversely affected wheat yields (Kingra, 2016). Across India, different wheat cultivars exhibit varying responses to climate change, with yield fluctuations being more pronounced in late-sown wheat and in the central-peninsular regions (Mohan, 2014). In the Indo-Gangetic plains, rice-wheat systems face sustainability challenges, as rice yields decline while wheat yields demonstrate an upward trend over time (Timsina et al., 1997). Climate change is anticipated to create regional disparities, with northern latitudes likely benefiting from warmer conditions, whereas sub-tropical and tropical areas are expected to experience increased heat stress and drought (Braun et al., 2009). Future priorities for wheat breeding must focus on enhancing yield, quality characteristics, and resilience to changing environmental conditions, leveraging advancements in molecular biology and sustainable management practices (Braun et al., 2009).

Crop rotation, diversification and ecological intensification: Long-term studies have shown that diversified crop rotations and the implementation of conservation agriculture practices can significantly improve agricultural sustainability.

Crop diversification enhances system robustness by increasing resistance to biotic and abiotic stresses, improving yield stability, and reducing weed pressure and disease severity (Li et al., 2019). Conservation agriculture practices, including crop rotations with legumes, can increase soil organic carbon stocks, enhance soil health, and improve crop productivity (Samal et al., 2017; Yang et al., 2024). Ecological enhancement measures, such as optimized fertilization and irrigation schemes, can increase crop yields while reducing environmental impacts such as nitrogen leaching and soil organic matter loss (Magwaza et al., 2022). Compared with traditional cereal monoculture, diversified rotations that include cash crops and legumes can increase equivalent yields by up to 38%, reduce N_2O emissions by 39%, and improve soil health by 45% (Yang et al., 2024). These practices provide promising solutions for sustainable food production and long-term agricultural resilience.

Evidence of system robustness based on long-term wheat experiments: Long-term experiments on rice-wheat systems in South Asia reveal complex sustainability challenges. While wheat yields have increased, rice yields have declined over time (Timsina et al., 1997). Climate change is projected to reduce yields of major crops in Africa and South Asia by an average of 8% by 2050, with wheat and maize particularly affected (Knox et al., 2012). The sustainability of rice-wheat systems is in question due to persistent yield declines and stagnant farmer yields in long-term experiments (Banu et al., 2011). However, diversified crop rotations can improve system robustness by increasing resistance to biotic stresses, improving resilience to abiotic stresses, and improving the stability of crop production (Li et al., 2019). Crop diversification increased system robustness by 14% compared to less diversified systems (Li et al., 2019). These findings highlight the importance of crop diversification and soil biological health in maintaining productivity in rice-wheat systems.

Cross-Country Comparisons and Regional Insights

This summary analyzes cross-country comparisons and regional insights derived from long-term wheat experiments conducted across Asia. Variations in cultural adaptations and coping strategies between rice and wheat farming regions in China significantly influence stress management and processes of accumulation (English and Geeraert, 2020). Climate risk assessments focused on winter wheat cultivation in the Great Plains of the United States reveal notable regional disparities in water deficit and temperature-related stresses, which in turn affect crop phenology and yield stability (Lollato et al., 2020). Furthermore, long-term studies conducted in China's North China Plain indicate a reduction in greenhouse gas emissions per ton of grain produced within wheat-maize rotation systems, thereby illustrating the potential to lower emissions without sacrificing yield outputs (Liang et al., 2021). Additionally, ultrasonic measurements of Asian noodles made from various classes and varieties of wheat in Canada demonstrate significant differences in dough properties, underscoring the critical role that wheat selection plays in noodle production (Sally et al., 2014). Collectively, these studies highlight the regional variability inherent in wheat cultivation and its implications for agricultural adaptation, climate resilience, and food production.

Comparative Analysis of Long-Term Wheat Experiment Findings Across Countries: This section synthesizes findings from four studies addressing agricultural practices in South Asian countries. In Bangladesh, India, Nepal, and Pakistan, wheat-based farming systems are experiencing substantial shifts in gender roles and decision-making processes; however, the degree of feminization varies significantly among these nations (Farnworth et al., 2023). The environmental impacts of agriculture in this region are marked by notable greenhouse gas emissions, with both rice and wheat production serving as major contributors (Sachdeva et al., 2023). Moreover, Livestock production in India, Bangladesh, and Sri Lanka also poses negative environmental consequences (Sachdeva et al., 2023). A comparative assessment of national intellectual capital across Pakistan, China, India, and Bangladesh reveals fluctuations in market, human, process, and renewal capital from 2014 to 2019 (Mirza and Qaiser, 2024). In Pakistan, an analysis of wheat supply responses indicates that production lags are attributable to adjustment difficulties and associated costs, with gross margin specifications exhibiting lower elasticities compared to those based on wheat specifications (Bhatti et al., 2011).

Policy and Socio-Economic Impacts: Papers in this series explore the long-term effects of various interventions and policies on socioeconomic outcomes, particularly in rural Asia. Quisumbing et al. (2011) evaluated the effects of anti-poverty programs in Bangladesh, including agricultural technology, education transfers, and microfinance on monetary and non-monetary well-being indicators. These studies highlight the importance of longitudinal data in evaluating intervention effects. Bhatti et al. (2011) analyzed wheat supply responses in Pakistan, highlighting the role of production lags and economic factors in farmers' decision-making. English and Geeraert (2020) studied how cultural context affects the coping strategies of students who migrate between rice-wheat rotation zones in China, showing that ecological factors have an important influence on stress management and adaptive capacity. Overall, these studies highlight the complexity of evaluating the long-term impact of policies and point out that multiple factors, including agricultural practices, cultural context, and local economic conditions, need to be considered when designing and implementing interventions.

Institutional Support and Knowledge Sharing: Long-term wheat studies in Asia have provided valuable insights into sustainable agriculture and global collaboration; for instance, the Magruder Plots experiment, which has been conducted for over a century, underscores the significance of soil fertility and genetic improvements in maintaining yields, even in the face of declining organic matter (Girma et al., 2007). In Central Asia, international collaboration has facilitated the development of resilient wheat varieties through sharing germplasm and knowledge (Morgounov et al., 2005). The Wheat Information System (WheatIS) facilitates data sharing and collaboration among wheat researchers worldwide (Sen et al., 2020). In rice-wheat farming systems, control of leaf spot disease has benefited from a multidisciplinary approach that combines genetic resistance, agronomic practices, and farmer involvement (Duveiller, 2004). These long-term experiments and collaborative efforts have made important contributions to understanding wheat production dynamics, improving crop management practices, and addressing regional challenges in wheat cultivation in Asia.

Integration with Crop Physiology, Ecology, and Agronomy

Long-term experiments yield important insights into sustainable crop production and ecosystem health. For instance, the Magruder Plots, established in 1892, demonstrate that continuous winter wheat production can be sustained for over a century without fertilization; however, this practice results in a significant decline in soil organic matter (Girma et al., 2007). Similarly, the Rothamsted experiments, which have been conducted for over a century and a half, provide evidence that consistent annual fertilization can both sustain and enhance grain yields in monocultures of wheat and barley (Jenkinson, 1991). These experiments provide critical data regarding the long-term effects of fertilizers on soil organic matter and nitrogen balances. In Asia, a long-term experiment focusing on rice-wheat systems in India has revealed a trend of declining rice yields alongside increasing wheat yields over time (Timsina et al., 1997). Furthermore, simulation models that are validated with experimental data can be utilized to analyze long-term trends in crop yields and soil fertility, thereby offering insights into the sustainability of agricultural systems (Timsina et al., 1997; Jenkinson, 1991).

Mechanistic Understanding from Long-Term Wheat Experiments: Crop-Environment-Management Interactions: Recent investigations into crop-environment-management interactions in Asia have highlighted the complexity of factors influencing wheat production and its adaptation.

Long-term experiments indicate that greenhouse gas emissions per ton of grain have decreased over the past two decades as a result of agricultural intensification (Liang et al., 2021). Dynamic crop growth models are currently being developed to predict complex traits, such as yield, under varying environmental conditions (Voorn et al., 2023). Studies focused on wild wheat have demonstrated significant longitudinal and latitudinal variations in flowering time, with early-flowering phenotypes evolving in response to environmental changes (Matsuoka et al., 2008). Additionally, research examining human adaptation in rice and wheat farming regions across China suggests that ecological factors significantly influence coping strategies, revealing that wheat-farming regions are more inclined towards environment-altering approaches, while rice-farming regions tend to emphasize environmental fit (English and Geeraert, 2020). These findings highlight the necessity of considering both environmental and cultural factors when studying crop-environment-management interactions.

Frameworks for Integrative and Systems-Based Approaches: Long-term experiments and systems-based methodologies are vital for enhancing our understanding of and improving the sustainability of rice-wheat systems in Asia. These systems face several challenges, including yield stagnation, soil degradation, and foliar diseases (Timsina et al., 1997; Duveiller, 2004). To address these concerns, integrative approaches that combine genetic improvement, agronomic practices, and soil management are essential (Duveiller, 2004; Beres et al., 2020). The Wheat Initiative's Expert Working Group on Agronomy aims to formulate a global research strategy focused on yield gap analysis and collaborative research initiatives that maximize the impact on wheat production systems (Beres et al., 2020). Zero tillage has emerged as a promising technology for enhancing sustainability in rice-wheat systems, with the potential to reduce resource degradation while maintaining productivity (Laxmi et al., 2007). Long-term experiments and simulation models are crucial for evaluating trends in yield, soil fertility, and overall system sustainability, providing valuable insights for the development of effective management strategies (Timsina et al., 1997).

Conclusion

Long-term wheat trials (LTEs) in Asia have provided valuable insights into sustainable agricultural practices, highlighting the importance of crop diversification, integration of organic and inorganic nutrient sources, and conservation agriculture in improving yield stability, improving soil organic carbon content, and enhancing resource use efficiency. Despite these advances, several knowledge gaps remain, especially the lack of region-specific data in Southeast Asia and the inadequate inclusion of socioeconomic and gender dimensions. In addition, the complex interactions between climate extremes and long-term soil-crop responses remain understudied. To address these issues, the next generation of long-term wheat trials should prioritize multi-site, multidisciplinary networks that integrate genetics, agronomy, and socioeconomic analyses; employ climate-smart experimental designs that reflect a range of stressors (e.g., heat, drought, and disease); develop advanced data systems to enable coordination and meta-analysis of long-term datasets; and promote farmer-led adaptive trials to link results from long-term wheat trials to actual operations and adoption dynamics. On the policy side, sustained support is essential to institutionalize LTT into national research infrastructure, promote public-private partnerships to scale up proven practices, incorporate findings from LTT into regional food security and climate adaptation strategies, and ensure inclusive access to technologies for smallholders and women farmers. Taken together, these measures are critical to translating scientific evidence into scalable and resilient solutions that strengthen the sustainability and productivity of wheat-based systems across Asia.

Acknowledgements

We gratefully acknowledge the contributions of many researchers, institutions, and the Long-Term Field Experiment (LTFE) network, whose continued efforts have made it possible to generate and maintain critical data on Asian wheat systems. We particularly thank the International Maize and Wheat Improvement Center (CIMMYT), the Indian Council of Agricultural Research (ICAR), and the national agricultural research systems of China, Bangladesh, Pakistan, Afghanistan, and Nepal for their fundamental role in supporting and managing the LTFE. Special recognition is given to the Rothamsted Research (UK), the Magruder Plots (USA), and the Morrow Plots (USA) for serving as global benchmarks and methodological inspirations. We appreciate the valuable insights from interdisciplinary collaborators working on agronomy, soil science, plant physiology, and climate resilience. This study was enriched by the contributions of scientists documenting wheat yield trends, soil nutrient dynamics, greenhouse gas emissions, and water use efficiency in long-term studies. We are also thankful for the scholarly efforts that have advanced modeling tools and statistical methods to interpret LTE data effectively. Lastly, we acknowledge the farming communities whose participation in adaptive trials and conservation initiatives has helped bridge experimental research and field-level application.

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