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Sustainable cereal production through integrated crop management: a global review of current practices and future prospects

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Among cereals, three crops namely maize, wheat, and rice account for 90% of the total cereal production, with global production levels of 791.2, 522.6, and 1229.63 million tons for wheat, rice and maize, respectively. The global challenges of food insecurity, climate variability, and unsustainable land use necessitate a redefined approach to cereal production, focusing on climate resilience, low vulnerability, and high productivity while establishing food and environmental safety. Integrated crop management (ICM) offers a holistic farming approach that integrates various agricultural practices to ensure long-term benefits and mitigate risks. This comprehensive review examined a total of 108 documented studies from existing literature pertaining to the last 23 years, besides case studies on ICM in rice, wheat, and maize production, analyzing its benefits, challenges, and future directions. In Asian countries, where rice is a staple food, ICM practices have effectively addressed challenges such as yield stagnation, declining profits, and crop failures. Nutrient and pest management, along with conservation agriculture (CA), have played a crucial role in overcoming these challenges. China's implementation of site-specific management duly integrated with other practices, has successfully reduced excessive nitrogen use besides improved environmental and health outcomes. Sustainable corn production has been achieved in the USA and Africa through comprehensive implementation of CA and crop diversification. Globally, ICM has demonstrated yield increases of 10–19% for rice, 16–30% for wheat, and 13.5–30% for maize crops. Despite having ample potential, the widespread adoption of ICM faces technical, climate-related, and economic constraints. Overcoming these challenges requires targeted training, extension services, and supportive policies. Furthermore, future research should focus on addressing key knowledge gaps to facilitate the widespread implementation of ICM. While promoting climatic resilience and sustainability in cereal production systems, ICM can contribute to food security and environmental preservation globally.

KEYWORDS

agro-ecological practices, soil health management, yield optimization, pest and disease control strategies, food security

1 Introduction

With over 700–800 million people uncertain about their next meal, the modern world is grappling with an unprecedented hunger and malnutrition crisis (FAO et al., 2022). The scale of this crisis has escalated drastically, with over 345 million people experiencing severe food insecurity in 2023, which is more than double the number in 2020. Factors such as conflicts, economic shocks, climate extremes, and rising fertilizer prices have combined to create an unprecedented food crisis (WFP, 2023). To ensure global food security, it is essential to manage and utilize resources like land, water, and nutrients sustainably, while also respecting planetary boundaries (Grote et al., 2021). Striking the right balance between food and nutritional security, environmental protection, and climate change mitigation poses a significant challenge for our food systems and the management of land and water resources (IPCC, 2019; Willett et al., 2019). Rice, wheat, and maize, the three staple crops, provide about 40% of our daily calories and form the foundation of human nutrition (Neumann et al., 2010; World Economic Forum, 2018). Although these crops contribute significantly to global cereal production, their current output falls short of meeting the requisite demand of a growing population, leading to significant environmental pressures (Vinci et al., 2022).

However, cereal production is not feasible without alarming consequences. It accounted for 18% of greenhouse gas emissions (GHGs) from the agro-food sector between 1961 and 2019 due to high reliance on synthetic pesticides, nitrogen (N) fertilizers, and the use of polluted irrigation water (Pillay et al., 2018; Hamel et al., 2020; Vinci et al., 2022). Addressing these environmental challenges, necessitates climate-smart agricultural practices that aim to reduce synthetic inputs, promote multiple production approaches, and enhance sustainability (Cambareri, 2017; Hamel et al., 2020). In this context, integrated crop management (ICM) emerges as a pragmatic approach to address the challenges associated with cereal production. ICM is a holistic farming approach that integrates various agricultural practices, including irrigation, nutrient management, pest management, and soil conservation (Choudhary et al., 2018; Singh et al., 2022). By combining these components, ICM could greatly optimize crop production, while minimizing negative environmental impacts (Math et al., 2018). It also offers several advantages over traditional methods, such as enhanced productivity, reduced input costs, improved soil health, pest and disease management, and resilience to climate variability (Ottoman et al., 1997; Khatun et al., 2018).

Despite these advantages, the full potential of ICM practices in cereal production remains largely unexplored due to various challenges. These challenges include high input costs (28–34%) associated with additional labor requirements, IPM practices, additional nutrient requirements in addition to lack of knowledge and awareness, resistance to change, limited government support, and climatic variability (Bagheri et al., 2019). Encouraging farmers to adopt ICM practices can revolutionize cereal production, besides protecting the health of individuals coupled with a safer environment. While some review papers have discussed the general question of feeding the growing world population, limited attention has been given to the specific role of staple food crops like rice, wheat, and maize (Shiferaw et al., 2011, 2013; Fukagawa and Ziska, 2019; Tadesse et al., 2019; Mishra et al., 2022). This review aims to fill that gap by exploring the ICM approaches being practiced in cereals globally, highlighting their challenges, and presenting futuristic directions for achieving sustainable cereal production while maintaining a cleaner and safe environment.

2 Background

The historical perspective of ICM can be traced back to the mid-20th century, when conventional agricultural practices heavily relied on chemical inputs (Blois, 2023). These systems were characterized by the intensive use of agrochemicals to maximize production, including extensive tillage, mono cropping, and limited recycling of materials (Sumberg and Giller, 2022). However, the overreliance and indiscriminate application of these inputs led to a range of environmental and health issues (Hemathilake and Gunathilake, 2022). The invention of organo-chlorine insecticides, particularly DDT, in the 1940's revolutionized pest control practices (Pimentel, 1996). This was followed by the green revolution in the 1950's and early 1960's, which brought about a complete transformation of agriculture and a significant increase in food production (Pretty, 2018). During this period, there has been a shift away from understanding pest phenology, density, and natural enemies, and synthetic pesticides and fertilizers were seen as "the sole answer to world hunger" (Penn State Extension, 2022). However, this approach led to a high level of dependence on chemicals, resulting in increased selection pressure on pests and the development of resistance. Consequently, this has necessitated a growing demand to explore production practices that were environmentally friendly, economically viable, and socially responsible.

The earliest known developments in literature regarding integrated pest management (IPM), ICM, integrated production (IP), and integrated farming (IF) emerged during the 1950's in many countries worldwide (Kneib and Schulz, 2006). Further research on IF in its various guises, such as integrated farming systems (IFS) and IPM, was conducted in the late 1970s (Rose et al., 2019). It was not until 1991 that ICM was first introduced as an attempt to address public perception of farming. In Great Britain, a new organization called linking environment and farming (LEAF) was formed with the aim of promoting good agriculture and reassuring consumers that the food they consumed was safe (Finch et al., 2014). In recent years, advancements in technology and the growing realization of the importance of regenerative agriculture have further propelled the adoption of ICM. Pioneering practices involving ICM, such as IP, IF, and IPM, have been developed as holistic concepts that encompass all crop and farming activities (Rossi et al., 2010). Furthermore, the integrated crop-livestock system (ICLS) has gained attention as an alternative management strategy that sustainably intensifies food production while benefiting producers, soil health, and the environment (Kumar et al., 2019). This historical perspective of ICM reflects a shift from conventional agricultural practices, which heavily rely on chemical inputs to a better holistic and sustainable approach. The integration of various practices, technologies, and ecological principles in ICM has allowed farmers to optimize crop production while minimizing environmental impacts and promoting long-term agricultural sustainability.

2.1 Global cereal production scenario

Cereals hold immense importance as the most traded commodities worldwide in terms of quantity, with the United States of America (USA) and Europe emerging as major exporters, while Asia stands as the largest importer (FAO et al., 2022). These crops cover half of the world's harvested area, spanning over a vast area of 736 million hectares (m ha), and contributing a staggered total production of 2,996 MT. Among cereals, maize, wheat, and rice play pivotal roles, accounting for approximately 90% of the total cereal production. Maize, with its versatile applications, stands as a key player in global agriculture. The USA takes the lead in maize production, boasting a remarkable output of over 360 MT. China and Brazil follow closely behind, with maize productions of 260 MT and 104 MT, respectively (FAOSTAT, 2022). Wheat, often considered the "staff of life," holds tremendous value in the global food system. China, India, and Russia have emerged as the major wheat producers, contributing significantly to the world's wheat production. China leads the pack with a wheat production of 135 MT, followed by India with 107 MT and Russia with 86 MT. The details have been given in Figure 1 for better presentation.

Rice provides a substantial portion of the energy for being consumed by 2,700 million people in Asia, with China securing the position of the largest rice producer, with an impressive output of 213 MT; while India closely follows (155 MT).Other major rice producers include Indonesia, Bangladesh, Vietnam, and Thailand (FAOSTAT, 2022). Its production demands effective management strategies, including IPM and water conservation techniques, to ensure sustainable cultivation and meet the dietary needs of millions. The global production scenario of these cereals highlights their critical role in ensuring food security, sustainable agriculture, and economic stability. The adoption of ICM practices in cereals therefore becomes imperative to address the challenges posed by population growth, climate change, resource constraints, and environmental concerns. By implementing sustainable and integrated approaches, farmers can enhance productivity, reduce environmental impacts, and contribute to a resilient and sustainable future of cereal production with cleaner environment.

2.2 Evolution of ICM practices in cereals

The evolution of ICM practices in cereals, including rice, wheat, and maize, has witnessed a transition from conventional methods to more sustainable and integrated approaches. The Food and Agriculture Organization (FAO) recognizes the significance and relevance of ICM, emphasizing its superiority over individual agronomic management approaches (Pooniya et al., 2022). However, specific practices may vary based on the crop and region. In rice production, the focus has shifted toward water management techniques aimed at optimizing water use efficiency (WUE) and reducing methane emissions. One promising technique is alternate wetting and drying (AWD), an economically viable and eco-friendly irrigation system (Ishfaq et al., 2020; Suwanmaneepong et al., 2023). AWD maximizes rainfall capture, reduces irrigation pumping, and maintains grain quality and yield (Howell et al., 2015; Henry et al., 2017). IPM strategies in rice emphasize upon biological control, resistant varieties, and cultural practices like synchronized planting, reducing the reliance on pesticides and promoting sustainable rice production (Enriquez et al., 2021).

In wheat production, there has been a greater emphasis on precision agriculture technologies, enabling targeted fertilizer application, site-specific crop management, and precise pesticide usage. Disease-resistant varieties, conservation tillage, and yield monitors are also utilized to ensure it (Mercer, 2019). Precision agriculture technologies can help farmers achieve consistent crops while reducing inputs like fertilizer and pesticides, thereby leading to improved sustainability and profitability (Finco et al., 2021). Maize production has also witnessed advancements in the use of cover crops (Effland et al., 2022), crop rotation, and intercropping, particularly with soybean (Iqbal et al., 2019). Optimized nutrient management practices have also been employed to enhance soil health and mitigate pest and disease pressures (Kumar et al., 2014a). Technological advances have played a significant role in increasing productivity and reducing costs on corn farms, ensuring food safety in regions where maize is a staple crop, such as East Africa (Mutiga et al., 2019). These advances have also contributed to the global expansion of maize production (Erenstein et al., 2022). Overall, the evolution of ICM practices in rice, wheat, and maize embraces a holistic and sustainable approach, incorporating site-specific technologies and practices to optimize yields, reduce inputs, and ensure long-term environmental and economic sustainability.

3 Methods

3.1 Search term strategy

In order to comprehensively assess the current practices and future prospects of ICM in sustainable cereal production, a systematic literature review was conducted. The search term strategy involved the following topics.

3.1.1 Keywords

Relevant keywords including "ICM," "IPM," "conservation agriculture (CA)," "water management," "soil fertility," and "nutrient management" were combined using Boolean operators to form the search string: '(ICM OR Integrated crop management) AND (IPM) AND (CA) AND (water management OR irrigation) AND (soil fertility OR soil health) AND (nutrient management OR fertilizer use efficiency)'. This string was used to retrieve the literature from various platforms such as *Google Scholar, J-gate, CAB direct*, and *Scopus*, covering the period from 2000 to 2023. This approach aimed to capture a wide range of scholarly works focusing on ICM practices within the context of specific cereal crops (rice, wheat and maize). In addition to academic databases, government websites and reports, notably the FAO and the U.S. Department of Agriculture (USDA), were extensively explored to gather valuable insights on ICM practices in cereal production. The search was conducted in English language to ensure accessibility and uniformity of the collected literature.

3.1.2 Publication filtering

After the initial collection of literature, a filtering process was employed to select publications that were most relevant to the objectives of this review. The filtering criteria included the (a) alignment of the publication with the scope of ICM in cereal

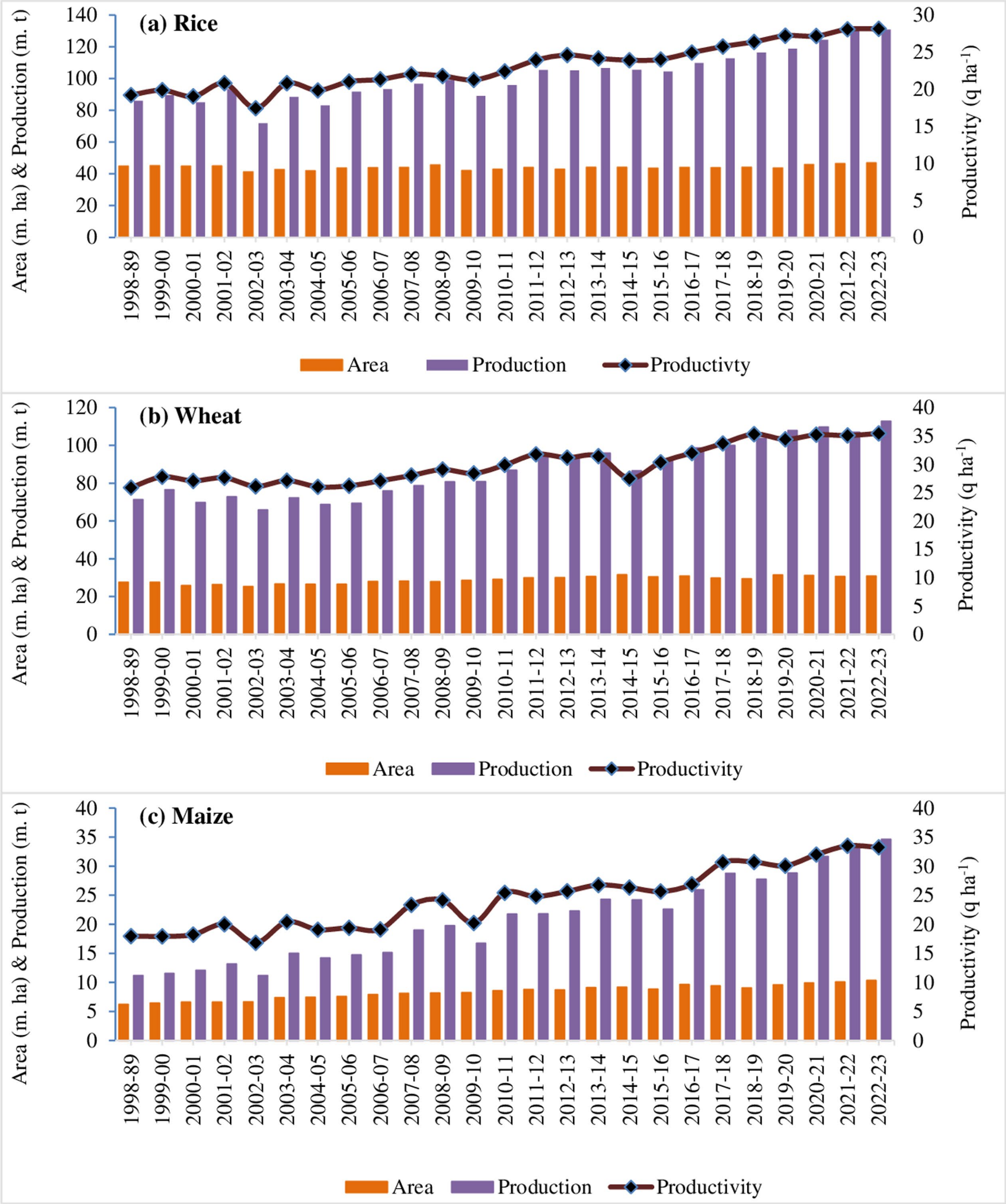

FIGURE 1
Area, production and productivity of **(a)** Rice, **(b)** Wheat and **(c)** Maize over the past 25 years. Source: Directorate of Economics and Statistics, DAC&FW, GOI (2023).

production, (b) publication within the time frame of 2000–2023, (c) peer-reviewed status to ensure research quality, (d) focus on maize, wheat, and rice production systems, (e) exclusion of duplicate records and non-English publications. This step ensured that the selected literature would provide valuable insights for the analysis.

3.1.3 Selection of publications

To effectively present the ICM approaches of cereals at the global level, a total of 45 publications for rice, 28 publications for wheat, and 35 publications for maize were selected from the filtered literature. The selection criteria included: (a) relevance to ICM practices, (b) coverage of key topics such as IPM, CA, water management, and NUE, (c) inclusion of studies that provided quantitative or field-based evidence on the effectiveness of ICM practices, and (d) recent publications to ensure up-to-date information. The rejection criteria included: (a) studies that lacked direct relevance to ICM or cereal production, (b) duplicate publications or studies that were reviews without original data or analysis, (c) non-peer-reviewed sources. This rigorous selection process ensured that the chosen publications were both significant and relevant for analyzing current practices and advancements in ICM approaches for sustainable cereal production.

3.2 Analyzing the information

Once the literature collection was completed, a detailed analysis of the gathered information was conducted. Given the limited availability of extensive literature on the global evolution and advancement of ICM practices in cereal production, this review endeavors to bridge the knowledge gap through a rigorous analysis that enhances our understanding of ICM's role in achieving sustainable cereal production. To enhance clarity and facilitate a better understanding, the collected literature was meticulously organized into subsections corresponding to specific cereal crops, namely rice, wheat, and maize, along with their respective ICM practices, background, challenges in adoption of ICM, success stories and future direction and recommendations. The analysis of the information aimed to achieve the objectives of this review, which included: (i) Evaluating current practices and challenges in cereal production, focusing on the adoption of ICM in rice, wheat, and maize. (ii) Analyzing success stories, challenges, and future research directions to foster sustainable cereal production through ICM; and (iii) Summarizing key findings to promote the widespread adoption of ICM practices in cereals.

4 Approaches to ICM in cereal production at global level

Agriculture contributes approximately 4% to the global gross domestic product (GDP) as per latest reports (Statista, 2023). In developing and developed countries, the agricultural GDP accounts for 8 and 25%, respectively (FAO, 2011). It is worth noting that around 2 billion people, comprising 26.7% of the world's population, depend on agriculture for their livelihoods (FAO, 2018). Agricultural development plays a crucial role in eradicating extreme poverty, promoting shared prosperity, and feeding the projected 9.7 billion people by 2050. Furthermore, growth in the agricultural sector is 2–4 times more effective in raising income level among the poorest segments of society compared to other sectors (The World Bank, 2023). However, the increasing demand for food production to sustain a growing population poses significant challenges to agriculture, exacerbated by climate change and current agricultural practices. In this context, redefining cultivation approaches that address food security and climate resilience becomes imperative. ICM serves the purpose by combining the best aspects of traditional methods with appropriate modern technologies to achieve a balance between economic crop production and positive environmental management (Choudhary and Rana, 2018). ICM is referred to by different names in different countries, i.e., integrated crop and resource management in Indonesia; integrated crop management systems in European Union (Bradley et al., 2002). ICM offers a holistic framework that could integrate various practices to optimize cereal production while minimizing environmental impacts. This article has intended to explore the diverse approaches to ICM in cereal production at a global level, highlighting the strategies and initiatives implemented in different regions.

4.1 ICM practices in rice

Rice is a staple food in Asia, contributing to 90% of total production (Fukagawa and Ziska, 2019). Southeast Asia, also known as the rice-bowl of Asia, employs diverse rice ecosystems and cultivation methods, including lowland, upland, aerobic, submerged, and the system of rice intensification (SRI) (Settele et al., 2018; Yuan et al., 2022). While these approaches provide food security and promote biodiversity conservation, rice farmers face challenges such as stagnating yields, declining profits, water and labor shortages, adverse weather conditions, besides environmental concerns (Balasubramanian et al., 2005). To address these constraints in rice, ICM has emerged as a promising solution, delivering 10–19% higher yields and 70% higher nitrogen use efficiency (NUE) compared to conventional practices (Regmi and Ladha, 2006; Chu et al., 2016; Biswakarma et al., 2021). The information appended in Table 1 presents a review of several ICM models adopted worldwide in lieu of global adoption of ICM practices in rice.

4.1.1 Soil fertility and nutrient management

ICM components like integrated soil fertility management (ISFM), integrated nutrient management (INM), site-specific nutrient management (SSNM), and green manuring improve soil fertility and nutrient management in rice cultivation, enhancing yields and long-term sustainability (Sharma and Sharma, 2004; Agegnehu and Amede, 2017; Urmi et al., 2022). Numerous studies mentioned in forthcoming paragraph highlight the significance of ICM and its components in enhancing soil fertility and nutrient management in rice.

In India focus areas include direct-seeded rice (DSR) with residue retention and improved nutrient practices, such as no-till (NT) and INM with 30% residue retention in the rice-wet to rice-dry system, leading to increased productivity and C: N sequestration in paddy soils of north-eastern India (Yadav et al., 2017; Biswakarma et al., 2021). Similarly, adopting ICM practices, such as increased plant density, decreased N application, and the use of alternate wetting and drying (AWD) irrigation has significantly improved agronomic nitrogen use efficiency (ANUE) of Chinese farmers (Chu et al., 2016; Wang et al., 2017). In Nepal, SSNM, practices based on leaf color chart (LCC) with a critical value of 4.0, and crop-need-based N application, have demonstrated substantial increases in NUE compared to farmer's practice (Regmi and Ladha, 2006). Indonesian rice farmers have also successfully adopted ICM practices tailored to their agro-climatic conditions, including improved nutrient management, young single seedling planting, and intermittent irrigation, resulting in higher yields and better net returns (Wardana et al., 2002).

4.1.2 Water management

Water is crucial for rice cultivation, but traditional practices like continuous flooding often lead to water wastage (Dixit et al., 2016). In

TABLE 1 Globally adopted ICM models in rice.

ICM model	Country	Remarks	Reference
Zero-till DSR with wheat and mungbean residues, application of 75% RDF (100:21.8:41.5 NPK kg ha^{-1}) as liquid bio-fertilizer, arbuscular mycorrhizal fungi, glyphosate and pendimethalin (PE) *fb* bispyribac and need based IPDM practices	India	Average 10–13% higher yields, 19–22% additional returns, positive impact on soil organic carbon in the Indo-Gangetic Plains of North-western India	Biswakarma et al. (2021)
33% increase in plant density spaced at 20 × 15 cm, 10% decrease in N application (270 kg ha^{-1}), 60–60 PK kg ha^{-1}, AWMD irrigating when soil water potential reaches −10 kpa at 15–20 cm depth, and 2–3 cm submergence during first week after transplanting and at the time of N top-dressing	China	Substantially improvement in sink size (total number of spikelets per m^{2}), productive tillers, root oxidation activity, leaf area duration, grain yield, NUE, and WUE in rice.	Chu et al. (2016)
Transplanting of single seedling at 20 × 20 cm, applying 2 t ha^{-1} cattle manure at the time of land preparation, split application of P, N application based on scale 4 reading of LCC, intermittent irrigation after the 1st soil surface cracks appear, i.e., every 7–10 days	Indonesia	Higher rice grain yields, improved N fertilizer efficiency, and 55% water savings leading to 2–3 times higher water productivity	Wardana et al. (2010)
Transplanting 18–25 days seedlings at 20 × 20 cm spacing @ 25 hills m^{-2} with 3–5 cm submergence, applying P & K using omission plot estimation, N as per crop need using LCC, 2 hand weedings, and applying furadon granule, malathion dust, phosphume, zinc phosphide for pest management	Nepal	66% yield increase compared to farmers practice in the Eastern-Gangetic plains of South Asia	Regmi and Ladha (2006)
Use pure and high quality seeds with at least 85% germination, proper land leveling, maintain at least 1 seedling/ hill at 10 DAT, 3–5 cm submergence at early tillering and grain filling stages, INM, IPM as needed, harvest, threshing, cleaning, grading and storage need to be done properly.	Philippines	Increased grain yield and gross returns	Cruz et al. (2005)
Row seeding with IRRI drum seeders, P and K application based on soil nutrient status, top-dressing of N using LCC, adoption of IPM and timely harvest to minimize post-harvest losses.	Vietnam	Improved yields and water use efficiency	Pham et al. (2005)

DSR, direct seeded rice; RDF, recommended dose of fertilizer; IPDM, integrated pest and disease management; PE, pre emergence; fb, followed by; LCC, leaf color chart; AWMD, alternate wetting and moderate soil drying; NUE, nitrogen use efficiency; WUE, water use efficiency; INM, integrated nutrient management; IPM, integrated pest management; IRRI, international rice research institute.

light of water scarcity, and the need to meet the food demands of Asia's poor population, improved water management practices are essential (Facon, 2000). IWM an integral component of ICM promotes better irrigation practices through AWD and intermittent irrigation. These practices ensure efficient water use, minimize wastage and ensure sustainable water resources for rice production (Khatun et al., 2018). In China, farmers are adopting alternate wetting and moderate soil drying (AWMD) in combination with other ICM practices to augment water productivity. Studies by Zhang et al. (2018) demonstrated that AWMD reduced water input by 15.4 to 16.5% and increased irrigation water productivity (grain yield/ amount of irrigation water applied) compared to flood irrigation. Similarly, Zhang et al. (2019) implemented AWMD from 10 days after rice transplanting until maturity, which resulted in 29.9% increase in grain yield besides a 17.1% reduction in total methane emissions. Chu et al. (2016) also reported an increase to the tune of 27–28% in WUE using AWMD compared to flood irrigation. Thus, AWMD has been a proven technique to be an effective alternative to continuous flooding, improving productivity, conserving water resources, and enhancing rice yields in China (Xue et al., 2013; Chen et al., 2021).

In Indian context, several water management practices such as AWD, SRI and drip irrigation are being implemented to optimize water use, conserve resources, and enhance overall water productivity in rice cultivation (Surendran et al., 2021; Mallareddy et al., 2023). Studies have revealed significant water savings of 78.05 and 63.66%, when irrigation was applied through SRI [i.e., water application whenever hairline cracks (very thin, surface-level cracks that form when the soil dries out and shrinks, often due to loss of moisture or compaction) appear in field] and intermittent irrigation, respectively (Islam et al., 2014). These practices have been scientifically proven to improve WUE compared to traditional continuous flooding methods, leading to enhanced sustainable water management and increased productivity in rice production in India (Das et al., 2014; Biswas et al., 2021). In addition to India and China, Indonesian farmers have also adopted intermittent irrigation as a component of ICM to attain the aforementioned benefits (Wardana et al., 2010).

4.1.3 Crop diversification

Current rice production practices in Asia, specifically including India, often rely on continuous cultivation of rice or the rice-wheat cropping system (RWCS). However, these practices pose several challenges, such as nutrient depletion, soil degradation, pest and disease buildup, water scarcity, and reduced resilience to climate change (Papademetriou, 2000). The RWCS is extensively cultivated over a 13.5 m ha area in Asia, with 57% share located in South Asia, particularly the Indo-Gangetic plains (IGP) (Ladha et al., 2009; Banjara et al., 2021). Recognizing the need for enhanced productivity, resource utilization, and sustainable agriculture, crop diversification in rice-based cropping systems (RBCS) has emerged as an effective strategy (Singh et al., 2012). Crop diversification is a crucial component of ICM in rice cultivation as it manages risks, enhances soil health and nutrient management, besides reducing reliance on a single crop (Zhao et al., 2015). In China, the inclusion of legumes as a winter crop in rice rotations has been widely practiced to reduce nitrogen losses, greenhouse gas emissions, and maintain economic and environmental benefits (Xia et al., 2016; Cai et al., 2018).

Field studies conducted in Thailand, China, and Vietnam have clearly demonstrated the benefits of growing nectar-producing plants around rice fields. These practices have resulted in significant reductions in pest populations, a 70% decrease in insecticide applications, a 5% increase in grain yields, and a 7.5% economic advantage (Gurr et al., 2016).

4.1.4 Resource conservation technology and conservation agriculture

Improper management of rice fields has led to soil degradation, including reduced soil organic carbon (SOC) and deficiencies of macro and micronutrients (Das et al., 2014). In China, the extensive use of N, super rice, and hybrid rice varieties has contributed to significant progress in rice production (Zhu and Chen, 2002; Cao et al., 2010). Nevertheless, excessive use of N fertilizer (330 kg ha^{-1}) to maximize yields has caused soil and environmental pollution (Zhou et al., 2016; Gu et al., 2017). Achieving a balance between high rice yields and minimizing environmental consequences has now become a priority in China (Chen et al., 2014). By implementing ICM practices such as reducing N fertilizer by 10% (270 kg ha^{-1}), increasing plant density by 25%, applying organic manures, and increasing tillage depth, N losses have been reduced by 47.8% compared to conventional practices (Chen et al., 2021).

In India, prominent RBCS include rice-rice, rice-wheat, rice-pulse, and rice-potato systems (Deep et al., 2018). Among these, the RWCS is prominent in NWI and plays a vital role in the country's food and nutritional security, contributing approximately 75% to the national food chain (Benbi and Senapati, 2010). However, continuous adoption of the RWCS has resulted in declining groundwater tables, soil degradation, and environmental issues. Puddling in rice cultivation, while effective for weed control, leads to soil structure damage and reduced permeability, negatively affecting subsequent crops like wheat. Similarly, stubble burning, a common practice to clear fields quickly, contributes to air pollution, greenhouse gas emissions, and the loss of valuable organic matter, posing significant health and environmental challenges (Dhanda et al., 2022; Khedwal et al., 2023). To ensure sustainable intervention in the RWCS and safeguard the food security of millions in South Asia, alternative agricultural practices such as direct-seeded rice followed by zero-tilled wheat (DSR-ZTW) need to be promoted. DSR-ZTW helps save irrigation water (20–25%), reduce production costs, and improve system yields (Raj et al., 2017; Jat et al., 2019). This CA-based ICM in the RWCS of the IGP in NWI helps enhance system productivity and soil health (Biswakarma et al., 2021). In the Northeastern region (NER) of India, continuous rice-rice (R-R) systems are being practiced due to abundant water availability (Yadav et al., 2016). However, farmers in the NER rely on sub-optimal fertilizer and manure application, primarily depending on inherent soil fertility and residue incorporation (Das et al., 2015; Patel et al., 2015). Nevertheless, climate change, frequent droughts, and occasional floods pose significant threat to farmers in this region. Conservation-effective tillage practices, such as NT, and INM with 30% residue retention have been found to be very effective in sustaining system productivity of these areas (Yadav et al., 2017). In addition to these practices, IWM and integrated pest and disease management (IPDM) through ICM are crucial for ensuring sustainable rice production in Asia. These approaches address the challenge of feeding the growing population while minimizing environmental impacts and preserving long-term agricultural productivity.

4.2 ICM practices in wheat

Wheat is a vital food source for approximately 35% of the global population (Grote et al., 2021). It is cultivated across diverse regions, including Europe, North America, and Asia. Wheat contributes 20% of the total calories consumed worldwide, and its versatility in culinary applications plays a crucial role in diets worldwide (Scott, 2014; Zhang et al., 2022b). While modern wheat varieties have high yield potential, conventional practices have led to soil degradation and reduced genetic diversity (Reynolds et al., 1994; Biswakarma et al., 2021). In response to these challenges, the FAO is actively promoting the adoption of ICM practices among wheat farmers globally, with the potential to increase crop yields by 16–30% globally (Tadesse et al., 2017; Zhang et al., 2020; Singh, 2022). The information in Table 2 provides an overview of various ICM wheat models implemented worldwide, and the following section discusses different approaches to facilitate the successful adoption of ICM in wheat production.

4.2.1 Soil fertility and nutrient management

The use of chemical fertilizers and manures has significantly increased global food production, with N fertilizers alone being responsible for a 40–60% increase in wheat yield (Erenstein et al., 2008). However, concerns have arisen regarding the low NUE of wheat crops and the environmental impacts of current nutrient management practices. The N recovery rate of wheat is approximately 35–45% (Raigar et al., 2022), and excessive N application can lead to decreased grain yields and increased N loss in the wheat-soil system (Kubar et al., 2022). While efforts to develop stress-resistant wheat varieties are ongoing, adopting ICM practices is considered the best approach to redefine nutrient management for safe and sustainable wheat production (Dobermann and Cassman, 2002). Several studies have demonstrated the positive response to ICM components such as INM, SSNM, and green manuring in improving wheat yields.

In Indian Punjab, Khurana et al. (2008) tested the potential of SSNM in irrigated wheat and found increased grain yield from 4.2–4.8 tonnes ha^{-1}, NPK accumulation of 12–20, and 13% higher returns compared to farmer's practice. Similar observations have been reported worldwide, highlighting the beneficial effects of SSNM on yield and quality (Jin and Jiang, 2002; Mauriya et al., 2013; Richards et al., 2015). In India, INM is widely adopted as a sustainable strategy under ICM, combining inorganic fertilizers with organic amendments such as *Azolla* compost, bio-fertilizers, and vermi-compost leading to improved wheat productivity and soil quality (Nehra et al., 2001; Devi et al., 2011; Bharali et al., 2017; Sharma et al., 2019). In China, excessive N fertilizer application by farmers aiming for high yields has resulted in reduced NUE and significant environmental impacts (Ju et al., 2009). Notably, in the North China Plain, wheat fields receive one of the most intensive N applications in the world, with farmers typically applying 300 kg N ha^{-1} (Cui et al., 2008). Consequently, China is focusing on precision N management in wheat to improve NUE without compromising yields by designing suitable integrated

TABLE 2 Globally adopted ICM models in wheat.

ICM model	Country	Remarks	Reference
Seed rate of 100 kg ha^{-1}, and optimum fertilizer dose of 120:60:40 kg NPK ha^{-1}, with full dose of PK and half of N as basal and remaining N as 2 equal splits at tillering and booting stage, weed control with sulfosulfuron + metsulfuron @ 40 g ha^{-1} as PoE after 1st irrigation at 25–30 DAS and irrigating at critical stages	India	Average increase in wheat productivity by 21.43% and improved returns	Singh (2022)
Zero-till wheat with mungbean and rice residues, application of 75% RDF (120:26:33 NPK kg ha^{-1}) as liquid bio-fertilizer, arbuscular mycorrhizal fungi, and weed control with glyphosate (PP); pendimethalin (PE) fb total PoE, and need based IPDM practices	India	Average 14–16% higher wheat yields, improved soil carbon dynamics, increased farm profits and water savings in the upper Indo-Gangetic Plains of North-western India	Biswakarma et al. (2021)
Seeding rate of 525 seed m^{-2}, 180:90:60 NPK kg ha^{-1}, all of PK and 33.3% of N as basal and remaining N at stem elongation stage, flue gas desulfurization gypsum @ 15 Mg ha^{-1} and cow manure 30 Mg ha^{-1}, combined with optimum pest, disease and weed management practices	China	Increased crop yield by 25.3–30.8% and N productivity by 97.6–109%, improved soil quality by lowering soil pH and Na^{+}, and increased soil organic carbon	Zhang et al. (2020)
Minimum tillage using two wheel tractor, sowing with seed drill, irrigating twice using flooding, PK application based on omission plot estimation and N as crop need based using LCC at critical value 4.0 and additional 25 kg N ha^{-1} when LCC value falls below 5	Nepal	Overall increment in yield, fertilizer use efficiency and returns	Regmi and Ladha (2006)
Early planting with seed rate @ 123 kg ha^{-1} with average final stand of 200 plants m^{-2}, N application at basal, tillering and foliar application at late boot stage, application of PGR (ethephon) and optimized cultural management practices	United States	Increased grain yield and protein content, reduced lodging and effective pest and disease control	Mohamed et al. (1990)

PP, pre plant application; PE, pre emergence application; PoE, post emergence application; IPDM, integrated pest and disease management; DAS, days after sowing; PGR, plant growth regulator; LCC, leaf color chart.

crop N systems. Several studies suggest adopting integrated crop and soil management strategies, such as improved cultivars, early sowing, and applying N fertilizer at the stem elongation stage rather than the re-greening stage, to increase yields and NUE (Lu et al., 2016; Cai et al., 2021; Kubar et al., 2022; Li et al., 2023).

4.2.2 CA and crop diversification

In recent years, wheat yields have either plateaued or shown slower growth due to intensive cropping and excessive use of chemical inputs (Michel and Makowski, 2013). The increasing threat of recurring droughts, worsened by climate change, further challenges global wheat production. In India, the practice of growing wheat as a *Rabi* crop (winter season crop) following rice, maize, and soybean often leads to delayed sowings and exposure to high temperatures during grain filling, resulting in lower yields (Lobell et al., 2013; Newport et al., 2020). Burning rice residues is a common practice due to difficulties in tillage and sowing, which negatively affects air quality and health (Abdurrahman et al., 2020). To address these challenges, ZTW cultivation is being recommended to promote timely sowing of the wheat crop and incorporate rice stubbles, thereby providing substantial yield benefits (Jat et al., 2019). Studies in India have supported the adoption of ICM practices, such as raised bed planting or CA, in wheat production for improved yields, reduced costs, and environmental sustainability (Kumar et al., 2014b; Biswakarma et al., 2021; Pooniya et al., 2022; Singh, 2022).

In the USA and China, large-scale, energy-intensive production systems have dominated wheat farming. However, concerns have emerged regarding their negative environmental impacts, prompting scientists to suggest alternative practices using ICLS for wheat production in these countries. Practices such as sod-based rotations, sod intercropping, and incorporating dual-purpose cereal crops have shown success in achieving sustainability in wheat production in the USA (Sulc and Franzluebbers, 2014). Similarly, including wheat in systems based on rangelands in China has proven to be effective (Hou et al., 2008). These practices aim to improve environmental outcomes while maintaining productivity and economic viability in wheat production systems.

4.2.3 Pest and disease management

Plant pests and diseases have a significant impact on crop yields globally, causing an annual loss of 20–40%. Wheat is particularly affected, with average yield losses ranging from10.1to 28.1%, while in case of severe infestations it may exceed 50% (Oerke, 2006; Savary et al., 2019). In north-west Europe, fungal diseases accounted for 25% of the total wheat yield gap (Laidig et al., 2022). The recurring losses caused by a set of five fungal diseases alone resulted in a loss of approximately 62MT of wheat production annually, representing 8.5% of the world's total wheat production (Chai et al., 2022). Continuous fungicide application is the predominant approach, though increased fungicide resistance poses challenges (Lynch et al., 2017; Jorgensen et al., 2018). ICM approaches offer solutions through strategies such as crop rotation, chemical and biological controls, and host plant resistance. Recent studies have also highlighted the effectiveness of these approaches, which utilize multiple methods to enhance pest and disease management in wheat (Pooniya et al., 2022).

One specific threat to wheat production is spot blotch, caused by *Cochliobolus sativus*, which significantly reduces yields in warmer non-traditional wheat-growing regions. This foliar disease annually results in substantial yield losses, averaging 15–20% in South Asia, and thus poses a threat to the livelihoods of millions of small farmers. With the increasing occurrence of heat stress in Asia, the level of disease damage is further amplified. Genetic improvement combined with integrated management strategies, such as using resistant varieties, timely seeding, appropriate fertilization, crop rotation, and judicious fungicide application etc. help to reduce yield losses caused by spot blotch (Duveiller and Sharma, 2009). Another economically important root disease of wheat worldwide is take-all, caused by the fungus *Gaeumannomyces graminis* var. *tritici* (Kwak and Weller, 2013). This disease affects the crop at all stages, and ICM practices such as late sowing, optimal planting, application of ammonical fertilizers, and straw burial have proven effective in controlling this disease (Colbach et al., 1997; Loyce et al., 2008). In addition to diseases, pests also cause significant yield losses in wheat (Daamen et al., 1989). Efficient crop management practices utilizing IPM approaches have been shown to effectively control pests (Malschi et al., 2015). For instance, a case study by Babendreier et al. (2022) in the Greater Mekong Subregion (GMS) of Southeast Asia demonstrated that implementing the IPM strategy led to 2–10% higher rice yields, a twofold increase in the abundance of natural enemies such as spiders, and 1.5 fewer insecticide applications.

4.3 ICM practices in maize

Maize, also known as the "queen of cereals," holds significant global importance and is cultivated in approximately 155 countries (Revilla et al., 2021). Due to the wide adaptability and versatility, serving as food grains, animal feed, fodder, and raw material for various industrial products it has earned title of being a miracle crop (Dass et al., 2008). However, the intensive tillage required for maize cultivation contributes to around 25% of the total production cost, resulting in reduced net income (Hobbs et al., 2008). Therefore, the challenge lies in developing alternative production systems that are climate and resource resilient, ensuring sustained crop yields in the long term (Gathala et al., 2011). In recent years, attention has shifted toward improved maize-based systems such as ICLS, SSNM, CA, and ZT. These practices have gained prominence due to concerns about natural resource degradation and the need to mitigate production costs (Pariz et al., 2011; Saharawat et al., 2012). Maize cultivation offers great potential for harnessing the benefits of these ICM practices, as evidenced by various models presented in Table 3.

4.3.1 Soil fertility and nutrient management

In many Asian countries, INM practices are being widely implemented, combining inorganic fertilizers with organic composts, green manures, and bio-fertilizers to improve soil quality and maize productivity (Abid et al., 2020; Bhandari et al., 2021). Studies conducted in India have clearly demonstrated the benefits of applying 25% recommended dose of fertilizer (RDF) in combination with bio-fertilizers, green manuring with sun hemp (*Crotalaria juncea*), and the incorporation of compost at an appropriate rate, which in turn have resulted in improved soil nutrient status, better physic-chemical properties, and increased maize yields (Kalhapure et al., 2013). Similarly, the adoption of SSNM in Vietnam has shown positive outcomes (Huan et al., 2011). The use of plant growth-promoting rhizobacteria (PGPR) and arbuscular mycorrhizal fungi (AMF) has

TABLE 3 Globally adopted ICM models in maize.

Parameter	Conventional practices	Integrated crop management (ICM)
Soil fertility	Heavy reliance on chemical fertilizers, leading to nutrient imbalances and soil degradation.	Combines organic and inorganic inputs, promoting balanced nutrition and improved soil structure and fertility.
Nutrient management	Generalized fertilizer application without soil testing, often resulting in inefficiencies.	Site-specific nutrient management based on scientific assessments like soil health cards for optimal nutrient use.
Water management	Inefficient irrigation methods, leading to water wastage and salinization.	Promotes efficient techniques like micro-irrigation, drip systems, rainwater harvesting, and scheduling based on crop needs.
Crop diversification	Monocropping dominates, increasing vulnerability to pests, diseases, and market risks.	Encourages diverse cropping systems, including rotations and intercropping with cereals, pulses, and horticultural crops.
Resource use efficiency	Overuse of inputs like water, fertilizers, and pesticides, reducing long-term productivity.	Focuses on precise and judicious use of inputs to enhance efficiency and reduce costs and environmental impact.
Pest and disease management	Sole reliance on chemical pesticides, leading to resistance and ecological imbalance.	Advocates integrated pest management (IPM), combining biological, cultural, and chemical controls to manage pests sustainably.
Conservation practices	Rarely adopted, leading to soil erosion and loss of organic matter.	Incorporates practices like minimum tillage, residue retention, and cover cropping to conserve soil and water resources.
Yield and productivity	Short-term yield gains but declining productivity over time due to resource degradation.	Maintains or improves yields sustainably through holistic management of inputs, pests, and environmental factors.
Economic viability	High input costs and diminishing returns in the long run.	Reduces input costs through efficient practices, improving profit margins for farmers.
Environmental impact	Contributes to environmental issues like water pollution, greenhouse gas emissions, and loss of biodiversity.	Minimizes environmental footprint by reducing reliance on synthetic inputs and adopting eco-friendly practices.

also been reported to enhance nutrient availability in maize cultivation in the USA (Adesemoye et al., 2008).

4.3.2 Crop diversification

Maize is a versatile crop that can be grown in diverse soil and climatic conditions, making it suitable for crop diversification. However, the intensive cultivation of maize in regions like Central US, combined with the vulnerability to climate change, increases the risk of extreme weather events such as drought (Ortiz-Bobea et al., 2018). Crop diversity has been increasingly recognized for its potential to mitigate risks associated with climate change (Renard and Tilman, 2019). Long-term studies in the US have demonstrated that farmers who adopt temporal and diverse crop rotations involving crops like alfalfa, rye, sorghum, and soybean observed improved yield besides regenerated soil health (McDaniel et al., 2014; Tiemann et al., 2015). Diverse crop rotations have led to significant increase of 28.1% in maize yields across different growing conditions and reduced yield declines during drought years by 14–89.9% in the USA (Bowles et al., 2020). Similarly, Renwick et al. (2021) also found that diversifying maize-soybean rotation with small grain cereals and cover crops not only mitigated maize water stress but also reduced drought-induced yield loss up to 17.1per cent.

In India, maize is grown throughout the year and serves as a solution to water scarcity and declining water tables in *Rabi* rice-growing regions of Andhra Pradesh, Karnataka, and Tamil Nadu states. It also acts as an alternative crop to mitigate heat stress in wheat cultivation in Northern India. Spring maize, grown after the harvest of potato and sugarcane, has emerged as a profitable alternative to summer rice in NWI (Dass et al., 2012). In Brazil, the ICLS is a preferred approach for maize crop diversification. ICLS involves using the same production area for both agriculture and livestock production, either simultaneously or sequentially, to optimize land and environmental resource utilization (Carvalho et al., 2010). In Brazil, diversification efforts focus on selecting appropriate cover crops, particularly grasses that produce high biomass, which can be used as mulch to enhance level of soil organic matter. This promotes nutrient cycling, specifically N and carbon replenishment, water retention, and overall soil improvement (Ryschawy et al., 2017). Intercropping grasses such as *Urochloa ruziziensis*, *Panicum maximum*, and *Brachiaria mutica* with maize facilitates greater nutrient cycling, contributing to the sustainability of agricultural systems (de Castro Dias et al., 2020; Mingotte et al., 2020; Silva et al., 2020).

4.3.3 Conservation agriculture and crop establishment methods

Maize cultivation is widespread globally, primarily in the America, Asia, Africa and Europe regions (Erenstein et al., 2022). During 2020, approximately one-third of global farms cultivated maize, with a majority (84%) being small farms (<2 ha) in Asia, Africa, and South America, while larger farms were found in the USA and Brazil (Erenstein et al., 2021; Lowder et al., 2021). These regions encompass diverse agro-ecologies, ranging from drought-prone rainfed areas in sub-Saharan Africa to temperate highlands in Africa and irrigated off-season maize production in South Asia's IGP (Indo-Gangetic Plain). To enhance the sustainability of maize production in these regions, conservation tillage and crop establishment methods are crucial. The US Corn Belt, spanning over 12 states with Iowa and Illinois serving as top corn producers, has witnessed the development of conservation tillage practices driven by the desire to reduce soil erosion and petroleum consumption (Campbell et al., 1984). Long-term conservation tillage practices in the US Corn Belt from 2005 to 2017 have also demonstrated a 3.3% increase in maize yield and an observed improvement in soil organic carbon sequestration (Deines et al., 2019). Several studies have also shown that minimum tillage practices, compared to conventional tillage, can significantly enhance maize yields and biomass returns in both mono cropping and rotation systems (Campbell et al., 1984; Mirsky et al., 2012; Fiorini et al., 2020).

The Songliao Plain in Northeast China, known for its black soils, has the largest maize cropland and is considered the nation's "breadbasket" (Wang et al., 2023). However, water limitation in this region leads to huge yield variability (Liu et al., 2013). Conservation tillage practices, such as NT or ridge tillage (RT), have been successfully adopted in Northeast China to enhance soil quality, fertility, and address water-related challenges (Liang et al., 2007; Lou et al., 2012; Zhang et al., 2015). In contrast, in arid zones like Xinjiang, where water scarcity is common, farmers are adopting plastic film mulching (PM) with drip irrigation instead of conservation tillage (Zhang et al., 2017). A meta-analysis on PM adoption revealed a significant increase in maize yield (36%) and NUE (34%) compared to conventional tillage. However, PM is suitable under specific hydro-thermal conditions (with precipitation <650 mm and temperature > 23°C), whereas conservation tillage can be applied under various environmental conditions (Zhang et al., 2022a). In India, which is also a major maize-producing country, different sowing methods such as raised bed planting, zero-till planting, conventional till flat planting, furrow planting, and transplanting have been used to achieve higher yields, cost reduction, and environmental sustainability (Choudhary et al., 2018).

4.3.4 Pest and disease management

Pests and diseases are significant threats to maize production globally, drastically impacting food security and economic stability. Insects like stalk borers and fall armyworm (FAW), and diseases like grey leaf spot, cause substantial yield losses besides reduced grain quality (Rahmawati et al., 2020). Factors such as monoculture, reduced or NT practices, excessive use of chemicals, and climate change have contributed to the severity of infestations, putting maize yields at risk. Integrated pest management, another component of ICM is essential for minimizing yield losses by managing insects and diseases below economic threshold levels (Nwilene et al., 2008). One notorious pest is the FAW, which poses significant global threat to maize crop, and many countries have adopted integrated methods to control it (Ahissou et al., 2021). This pest can cause extensive damage by feeding on maize plants, leading to yield loss and consequently financial hardships for farmers. In India, FAW has been first identified in Karnataka in 2018 and became an invasive pest. The Indian government has developed an IPM package that includes cultural, biological, chemical, and mechanical methods to control this pest (Kumar et al., 2014c). Effective control measures for FAW include monitoring, early-stage neem oil spray, pheromone traps, release of natural enemies like *Trichogramma pretiosum*, and judicious chemical use such as Spinosad and Emamectin benzoate (Mooventhan et al., 2019). In Cameroon, an IPM approach incorporating cultural practices, chemical control, botanical products, push-pull farming, and biological control have been employed to control FAW (Akeme et al., 2021).

Combined management options, such as conventional tillage, intercropping, and resistant varieties, have proven effective in reducing grey leaf spot severity and increase maize yield in Tanzania (Lyimo et al., 2012). Similarly, various ICM practices have effectively controlled different types of maize stalk borers by combining cultural, biological, and chemical control methods in a holistic and sustainable manner (Ndemah, 1999). By implementing these integrated approaches, farmers can reduce reliance on chemical pesticides, minimize yield losses, and ensure the long-term maize productivity (Mooventhan et al., 2019).

5 Success stories in adoption of ICM in cereals in various countries

ICM practices in cereal production have shown promising results worldwide, thus demonstrating their vast potential to enhance agricultural sustainability and productivity. For instance, India and China observed increased corn yields by 20–30 and 13.5%, respectively by employing ICM over farmer practices while minimizing the production costs (Wang et al., 2017; Wani et al., 2017). Few distinguished success stories have been mentioned below for a better understanding.

5.1 ICM for sustainable maize production in Zambia

In Zambia, the conservation agriculture scale up (CASU) project has been launched in alliance with the ministry of agriculture and FAO (Baudron et al., 2007). This initiative promoted ICM practices, including minimum tillage, legume-based rotations, crop residue retention, and precision input application primarily to ensure sustainable maize production among smallholder farmers. The program aimed to benefit approximately 229,000 Zambian farmers, with a particular emphasis on empowering women. While the program successfully reached its target farmer base, its actual impacts varied. Many farmers reported significant yield improvements, with some experiencing up to double maize yields compared to traditional practices. However, challenges such as inconsistent adoption of practices, limited access to inputs, and variable climatic conditions constrained the full realization of its goals, particularly regarding widespread long-term sustainability and gender-specific outcomes (Baudron et al., 2007; FAO, 2019; Listman, 2022).

5.2 ICM for sustainable rice production in Vietnam

Vietnam heavily relies on rice cultivation for socio-economic development, with more than 15 million smallholder farmers depending on rice as their primary source of income. However, conventional rice production practices in Vietnam have been resource-intensive and have led to low-quality output (IFC, 2019). To address these challenges, Rikolto, an international NGO, initiated a project to promote sustainable and inclusive rice production through ICM practices (Rikolto, 2023). This project aimed to improve the livelihoods of nearly 2 million smallholder farmers, particularly in the rice-rich Mekong Delta region. Farmers received training and support in adopting ICM practices, such as efficient nutrient management and simplified crop management techniques. While the project succeeded in training thousands of farmers and improving awareness of sustainable farming methods, its actual impacts varied. According to project assessments, many participating farmers reported moderate increases in income due to reduced input costs and better yields. However, achieving the scale of 2 million farmers proved challenging, with actual adoption rates lower than expected due to barriers such as limited access to inputs, financial constraints, and traditional farming habits. Despite these challenges, the project demonstrated measurable improvements in rice quality and sustainability practices, contributing positively to the livelihoods of a significant portion of the targeted farmers (IFC, 2019; Rikolto, 2023).

5.3 ICM for sustainable rice and wheat production in Philippines

The Philippine Rice Information System (PRiSM) project has been implemented to enhance rice production through ICM practices (Wang et al., 2017). This project utilizes remote sensing technology to monitor rice fields and provide farmers with real-time information on crop growth, pest infestations, and nutrient deficiencies. Equipped with this information, farmers can make informed decisions regarding crop management, including fertilization timing, pest control measures, and water management. The PRiSM project has successfully increased rice yield besides reduced production costs at farmer's fields. Furthermore, ICM practices have also been explored in wheat production in the Philippines, where studies have demonstrated improved grain yield, better radiation use efficiency, and enhanced NUE in double-season rice crop. Overall, ICM practices have shown potential to bridge the yield gap and increase production in rice and wheat farming in the Philippines (Wang et al., 2017).

5.4 Farmer field school of ICM in Indonesia (FFS-ICM) for sustainable maize production

In Indonesia, the FFS-ICM program was launched in 2009 to improve corn production, drawing inspiration from the previous Farmer Field School of Integrated Pest Management (FFS-IPM). This initiative aimed to achieve self-sufficiency in rice and maize production. The FFS-ICM program provides farmers with training and capacity-building on ICM practices, encompassing efficient water management, balanced nutrient application, and proper crop residue management (Kariyasa and Dewi, 2013). Studies have indicated that the FFS-ICM program has led to increased corn productivity and improved input use efficiency in Indonesia. The success of the FFS-ICM program is contingent upon available infrastructure and government support in the respective implementation areas (Kariyasa, 2014). Overall, the FFS approach in Indonesia has served as a successful model for promoting ICM practices, resulting in improved crop yield, reduced production costs, and enhanced farmer income while fostering sustainable and inclusive agriculture (Van den Berg et al., 2020).

5.5 ICM for sustainable cereal production in India

India has successfully implemented ICM practices in cereal production, particularly in rice and wheat crops. One notable success story is the implementation of IPM practices by the consortium for e-resource in agriculture (CeRA) which played a significant role in promoting sustainable pest management practices, focusing on the use of biological control methods such as bio-pesticides and natural enemies (Pretty and Bharucha, 2015). This initiative has led to successful pest control outcomes in rice and wheat crops, particularly in the northwestern parts of the country (Vennila et al., 2016; Singh and Jasrotia, 2020). In the Nellore district of Andhra Pradesh, the adoption of SRI practices has resulted in increased rice yields by 29% and a remarkable 40% reduction in water usage. This has improved food security, reduced production costs, and increased income of rice farmers in the region (Adusumilli and Laxmi, 2011).

Similarly, in wheat production, the Punjab State Farmer's Commission has actively promoted ICM practices to address declining soil fertility and curb excessive reliance on chemical inputs. Farmers in Punjab have adopted practices such as CA, balanced nutrient management, and IPM, leading to wheat yield increase of 20–30% and enhanced resource use efficiency, ultimately leading to sustainable intensification of wheat farming (Bagheri et al., 2019; Pooniya et al., 2022). Likewise, the Bihar rural livelihoods promotion society (BRLPS) has implemented an ICM project focused on maize production in Bihar (Vennila et al., 2016). This project aims to promote practices such as CA, INM, and improved seed varieties. Consequently, maize farmers in Bihar have experienced increased yield, better soil moisture conservation, and enhanced nutrient use efficiency, leading to improved food security, increased incomes, and enhanced resilience for smallholder farmers. These success stories highlight the immense potential of ICM practices in cereal production to enhance productivity, conserve resources, reduce environmental impact, and improve the livelihoods of farmers. By adopting a holistic and knowledge-based approach, farmer's can establish sustainable and profitable cereal production systems (Bagheri et al., 2019).

6 Soil health card scheme and its role in enhancing ICM adoption

The Government of India introduced the Soil Health Card (SHC) scheme in 2015 to encourage balanced fertilizer use and promote sustainable agricultural practices. This initiative involved nationwide soil testing and the distribution of SHCs to farmers, offering crop-specific fertilizer recommendations tailored to improve productivity and reduce costs. The scheme has reached approximately 120 million farmers, with soil samples analyzed in laboratories across the country. SHCs provide critical data on soil's physical and chemical characteristics, including soil type, GPS location, farm size, and 12 essential parameters. These cards also recommend suitable crops based on the soil's nutrient status, enabling precise fertilizer application and sustainable land use. A notable impact of the SHC scheme is its contribution to reducing fertilizer misuse and improving crop yields. Pilot studies conducted in Karnataka and Andhra Pradesh demonstrated significant increases in productivity, with yield improvements of 31–45% in chickpeas, 15–16% in cotton, 12–15% in paddy rice, and 8–9% in sugarcane (Chander et al., 2014; Fishman et al., 2016; Raju et al., 2015).

These outcomes align closely with the nutrient management principles of ICM, which emphasize site-specific, scientifically guided nutrient application. Furthermore, the scheme promotes the adoption of organic fertilizers and bio fertilizers, supporting soil health restoration while reducing reliance on synthetic inputs (Reddy, 2019). The SHC initiative also plays a vital role in enhancing farmer awareness and building capacity, both critical for strengthening ICM adoption. By educating farmers about soil health and its direct link to productivity, the scheme motivates the transition from conventional practices to resource-efficient and environmentally sound approaches. Additionally, its emphasis on balanced fertilization helps address economic challenges, such as high input costs, by enabling smallholder farmers to use resources more effectively. As a replicable model, the SHC scheme has significant potential for adoption in other developing countries facing challenges like soil degradation and nutrient imbalances (Reddy, 2019). Its integration into broader ICM frameworks offers a pathway to sustainable cereal production, improved soil health, and long-term agricultural resilience. This synergy between the SHC scheme and ICM accentuate the importance of policy-driven interventions in overcoming adoption barriers and fostering sustainable agricultural systems (Table 4).

TABLE 4 Comparison of conventional practices and integrated crop management approaches.

ICM model	Country	Remarks	Reference
Zero-till raised bed maize with wheat residue, seed treatment with liquid bio-fertilizers, 75% RDF (150:26.2:50 NPK kg ha^{-1-100}% RDF), IWM with glyphosate (PP), atrazine (PE) fb mulch, need based IPDM are followed	India	Achieved 7.8–21.3% higher maize yields, 24.3–27.4% additional returns, and improved soil properties, i.e., soil organic carbon, microbial biomass carbon	Pooniya et al. (2022)
Intercropping maize with forage crops such as *Panicum maximum*, need based nutrient, pest and disease management.	Brazil	Increased returns and achieved sustainability by adopting integrated crop livestock system	Mingotte et al. (2020) and Silva et al. (2020)
Maintaining plant density of 76,000 plants ha^{-1} at spacing 60 × 22 cm, NPK application based on SSNM, and adjusting N using LCC, pest management using IPM and combined to bio-insecticides	Vietnam	Higher yields and improved NPK and organic matter of the soil	Huan et al. (2011)

RDF, recommended dose of fertilizer; IPDM, integrated pest and disease management; PP, pre-plant application; PE, pre emergence; fb, followed by; SSNM, site-specific nutrient management; LCC, leaf color chart; IPM, integrated pest management.

7 Inclusion of pulses in ICM for sustainable agriculture

The incorporation of pulses, or grain legumes, into ICM systems offers substantial potential to enhance agricultural sustainability. Pulses contribute significantly to environmental health through their unique traits, such as biological nitrogen fixation, reduced greenhouse gas emissions, minimal reliance on synthetic fertilizers and pesticides, and high water-use efficiency. Additionally, their ability to naturally enrich soil fertility aligns seamlessly with the core principles of ICM, which prioritize balanced nutrient management and soil health restoration (Reddy et al., 2023). Integrating pulses into cereal-based cropping systems, such as rice-wheat or maize-wheat rotations, provides both agronomic and environmental benefits. Diversifying crops with pulses reduces the prevalence of pests and diseases, improves soil structure, and enhances water efficiency. Practices like intercropping cereals with legumes or including pulses in crop rotations disrupt monoculture cycles, leading to increased soil organic matter and reduced land degradation (Kumar et al., 2023). These measures contribute to sustainable productivity and resilience, particularly in regions with resource constraints or vulnerability to climate variability.

Pulses are also integral to addressing food and nutritional security. Rich in protein, essential amino acids, and micronutrients, they are a critical dietary component, especially in developing countries such as India. Their inclusion in ICM systems not only supports sustainable farming practices but also diversifies farmers' income sources while improving dietary quality (Hussain et al., 2023). Policy interventions, including subsidies for pulse cultivation and the promotion of bio fortified pulse varieties, have further incentivized their adoption within ICM frameworks. Integrating pulses into ICM facilitates the creation of balanced and sustainable agricultural systems, conserving natural resources, mitigating the effects of climate change, and contributing to global food security objectives. By incorporating pulses, ICM systems can achieve enhanced productivity, ecological balance, and economic viability, ensuring long-term agricultural sustainability.

8 Challenges in implementation of ICM in cereal production

The successful implementation of ICM practices in cereal production faces several obstacles globally. These can be categorized into technical, economic and climatic barriers, which must be addressed to achieve sustainable and resilient cereal production systems.

8.1 Technical challenges

One major technical challenge is the limited knowledge and skills necessary for effective implementation of ICM. Farmers, especially in developing nations, lack access to up-to-date information and training on IPM, INM, and other sustainable practices. This knowledge gap hinders their ability to embrace and execute ICM practices in an effective manner (Bagheri et al., 2019). For example, the emergence of FAW (*Spodoptera frugiperda*) as a major maize pest in Sub-Saharan Africa has caused significant yield losses (Matova et al., 2020). However, farmers in this region are still struggling to adopt IPM practices due to limited knowledge and access to appropriate control measures (Otim et al., 2021). Additionally, adapting ICM practices to site-specific conditions also poses a challenge. The applicability of ICM practices varies across regions due to differences in climate, soil types, and pest dynamics (Matteson, 2000).

Developing site-specific ICM recommendations and adapting them to local conditions can be particularly challenging in areas with limited scientific resources and research infrastructure especially when managing the disease pest interactions in Asian rice cultivation (Gianessi, 2014). To overcome these technical challenges, it is essential to enhance farmers' technical knowledge through training and extension services. Extension support plays a pivotal role in promoting the adoption of new technologies among staple crop farmers. Developing region-specific ICM recommendations can immensely help crop growers in customizing ICM practices to suit their specific environments. Finally, improving data collection and monitoring systems can support evidence-based decision-making and the assessment of ICM practices outcomes (Pooniya et al., 2022).

8.2 Economic challenges

Farmers globally face various economic challenges when adopting ICM practices in cereal production. One significant issue is the upfront investment required for equipment, training, and other resources. Limited government support, such as subsidies and extension services, further hinders adoption (Rizal and Nordin, 2022). For instance, transitioning from conventional to ICM practices may entail additional costs, creating uncertainty about the economic feasibility of the transition (Bradley et al., 2002). Additionally, farmers face financial barriers, such as limited access to credit and financial services. Crop growers may struggle to secure loans due to factors such as lack of collateral, high-interest rates, and complex loan procedures (Viatte, 2001). While economic challenges relate to broader structural costs and policy gaps, financial challenges specifically pertain to the ability of individual farmers to access funds. Overcoming these interconnected burdens requires targeted financial incentives, a combination of policy interventions, and education and training programs to help farmers adopt ICM practices more effectively in cereal production (Bagheri et al., 2019).

8.3 Climatic barriers

Climatic barriers in implementing ICM practices arise from diverse and unpredictable weather conditions. Regions with erratic rainfall patterns like parts of Sub-Saharan Africa, may struggle with precise timing of irrigation and nutrient application (Bagheri et al., 2019). Extreme weather events like droughts, floods, and heat waves can disrupt ICM implementation and pose serious risks to crop productivity. Climate change can increase the incidence of crop diseases, which may affect yield drastically (Richard et al., 2022). Furthermore, changing climatic conditions alter pest, disease, and weed dynamics, making it challenging to adapt ICM strategies (Ahmed et al., 2019).

Overcoming climatic barriers requires climate-resilient approaches that account for local climatic conditions, such as utilizing drought-tolerant crop varieties, implementing water management strategies, and adhering to adaptive ICM practices that consider the changing climate dynamics. Additionally, the integration of climate information and early warning systems can assist farmers in making informed decisions regarding the timing and implementation of ICM practices in cereal production (Bakar et al., 2020).

The above mentioned challenges pose serious hurdles to the widespread adoption of ICM practices in cereals at the global level. Overcoming them requires collaborative efforts, including training and extension services to enhance technical knowledge, innovative financing mechanisms, climate-resilient approaches, supportive policies, and socially inclusive approaches to empower farmers and foster sustainable agricultural practices (Pooniya et al., 2022).

9 Futuristic research priorities

As the field of ICM in cereal production continues to advance, there has been an immense potential for improving cereal yields through the adoption of these practices. However, despite its established importance, ICM has not received the required attention it deserves. Several factors contribute to this, including the prevalence of conventional agriculture paradigms, limited awareness and understanding of ICM among farmers and policymakers, and the lack of supportive policies and incentives for its widespread adoption. Addressing these challenges requires focused research and efforts to disseminate knowledge (Bagheri et al., 2019). For successful implementation of ICM in cereal production and to achieve sustainable outcomes, it is crucial to address key knowledge gaps. Firstly, comprehensive studies are requisite to understand the interactions and synergies between different ICM practices in cereals. This includes investigating the combined effects of soil and nutrient management, water management, and pest and disease management on yield and sustainability. Additionally, further research is required to optimize the timing, dosage, and application methods of inputs, such as fertilizers, pesticides, and water, aiming to improve efficiency and minimize environmental impacts (Bradley et al., 2002). Moreover, there is a lack of knowledge regarding the long-term impacts of ICM practices on soil health, biodiversity, and ecosystem services. Therefore, comprehensive and multi-year studies are necessary to evaluate the long-term sustainability and resilience of ICM systems (Richard et al., 2008).

To prioritize the advancement of knowledge in this field, future research endeavors should focus on addressing key knowledge gaps and specific research needs to effectively implement ICM and achieve sustainable cereal production. Firstly, there is an urgent need for increased on-farm and participatory research to validate and adapt ICM practices according to local agro-ecological conditions and farming systems, ensuring their practicality and efficacy. This approach would help in tailoring ICM techniques to specific niches/contexts. Secondly, it is crucial to develop and evaluate innovative and context-specific ICM technologies and approaches, such as precision agriculture, digital platforms, and decision support systems. These advancements will enable real-time monitoring and data-driven decision-making in cereal production. Emphasizing the utilization of these tools can significantly enhance productivity and sustainability. Furthermore, interdisciplinary research is necessary to integrate agronomy, ecology, socio-economics, and policy analysis. This comprehensive approach will enable a deeper understanding of the barriers and incentives that influence farmer adoption of ICM practices. Such insights will inform the design of effective policies and strategies to promote ICM (Pooniya et al., 2022). It is essential to involve farmers and other stakeholders in the development of these practices to ensure their social acceptance and alignment with local community needs. Additionally, it is vital to develop practical methods that can deliver similar benefits across large areas without relying solely on site-specific modeling or extensive crop monitoring. By doing so, the scalability and widespread adoption of ICM practices can be facilitated, to enhance crop yields, sustainability, and resilience in the face of changing climatic and environmental conditions. While addressing these research needs and knowledge gaps, future efforts can lay the foundation for the widespread adoption and effective implementation of ICM in cereal production. This, in turn, will lead to improved yields, and enhanced sustainability, ultimately contributing to the overall goal of meeting global food demand besides minimizing environmental impact.

10 Conclusion

This review has attempted to provide a comprehensive analysis of existing knowledge on ICM practices, identifies challenges, and proposes future research directions. It highlights the positive impacts of ICM practices and various models adopted in rice, wheat, and maize production across different countries. Notably, India and China serve as exemplary cases of effective ICM implementation, achieving significant increase in corn yields by 13.5–30%. This success elucidates the potential of ICM in addressing challenges like the problem of RWCS in Asian countries through improved practices like DSR-ZTW and crop diversification. Beyond Asia, African nations have also benefited from ICM in maize production, with ICLS contributing to the sustainability of livelihoods. The United States has set an example by successfully adopting CA and diversification in wheat and maize production. Despite limited research on holistic approaches in cereal production, ICM holds tremendous potential for enhancing sustainability and climatic resilience. To effectively upscale ICM and realize its full potential, a clear "theory of change" is necessary. This includes addressing critical bottlenecks such as limited resource access, poor knowledge dissemination, and farmer resistance. Overcoming these challenges requires both technological and social interventions. Technologically, region-specific, cost-effective innovations such as DSR, ZTW, and precision agriculture tools can improve the accessibility and efficiency of ICM. On the social front, strengthening community-level networks and agricultural extension services, offering training, financial incentives, and policy support, will encourage adoption. Social acceptance can further enhanced by incentivizing early adopters and fostering knowledge exchange. By integrating these strategies, ICM practices can promote sustainable cereal production, improved yields, environmental conservation, and better farmer livelihoods.

Author contributions

VY: Writing – review & editing, Investigation, Resources, Validation, Visualization, Writing – original draft. KS: Conceptualization, Funding acquisition, Investigation, Resources, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. MA: Resources, Writing – review & editing. AE: Conceptualization, Funding acquisition, Investigation, Resources, Supervision, Validation, Writing – original draft, Writing – review & editing.

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