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Investigating the Amount of Quantitative and Qualitative Loss of Wheat and Ways to Reduce it

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ABSTRACT

This review article provides a comprehensive analysis of wheat losses across the supply chain, from pre-harvest to post-harvest stages, and explores strategies to mitigate these losses to enhance global food security and sustainability. Wheat, a vital cereal crop, faces significant quantitative and qualitative losses due to factors such as pests, diseases, inefficient agricultural practices, inadequate storage, and environmental challenges. In developing countries, losses are predominantly concentrated at the farm level due to limited access to modern technologies and infrastructure, while developed countries experience higher losses during the consumption phase. The review highlights the importance of adopting advanced technologies and sustainable practices to reduce losses. Mechanized harvesting, when properly calibrated, can minimize grain shedding and breakage, while modern storage solutions like expanded metal silos and controlled-environment systems can prevent spoilage and pest infestations. Solar-powered drying methods and biodegradable packaging materials offer environmentally friendly alternatives to traditional practices. Pre-harvest interventions, such as cultivating high-yielding and pest-resistant seed varieties, optimizing planting practices, and improving soil health, are also critical for reducing losses at the source. Furthermore, the review emphasizes the need for integrated approaches, including farmer education, policy support, and cross-sector collaboration, to address wheat losses effectively. By implementing evidence-based solutions tailored to local contexts, stakeholders can enhance food availability, reduce economic pressures, and promote environmental sustainability. This review serves as a roadmap for minimizing wheat losses, ensuring a resilient and efficient supply chain, and contributing to global food security for future generations.

1. Introduction

The supply and demand for food are pressing issues for humanity, especially with the global population on the rise. Recent estimates suggest that the world population could grow from about 7 billion to 9.7 billion by 2050 (Østergaard, 2024), with most of this increase occurring in developing countries (Dong et al., 2019). To meet this growing demand, we can either boost farm productivity or work on reducing food waste. Cereals, in particular, face significant losses and waste throughout the food supply chain. After fruits and vegetables, cereals are the second most important crop worldwide, with around 30% of their production being lost (FAO, 2022). Several factors contribute to these losses, including pests and diseases (Hollaway et al., 2013), adverse weather conditions, poor agricultural practices, and limited access to storage and transportation facilities (Mesterházy et al., 2020).

Wheat stands out as one of the leading cereal crops globally, playing a crucial role in the economy as a food commodity. It is also a vital source of fiber, protein, and other essential nutrients necessary for human health (Shewry & Hey, 2015). In Iran, wheat is a staple food that significantly influences the country's economy, culture, and culinary practices. For instance, in 2020, Iran produced 15 million tons of wheat, which represented about 20% of the country's total agricultural output (FAO, 2022). Table 1 highlights the wheat production figures for the top producers, with a particular focus on Iran.

Published statistics indicate that over 50% of our daily calorie intake comes from cereals (Laskowski et al., 2019). Therefore, protecting cereal crops is a crucial strategy to meet our nutritional needs and alleviate economic pressures (Nath et al., 2024). The cereal supply chain can be divided into two main segments: on-farm and off-farm activities (Ekepu et al., 2017). On-farm activities, whether semi-mechanized or fully automated, include harvesting, threshing, cleaning, drying, storage, packaging, and transportation to markets.

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Off-farm activities primarily involve handling, packaging, storage facilities like warehouses and silos, marketing systems, and consumption (Nawi et al., 2010). In developed countries, the largest losses of cereals occur during the consumption phase, while in developing countries, most losses happen in the earlier stages, particularly on the farm (Costa, 2014). Each stage of the supply chain, from harvest to consumption, experiences losses, but many of these can be mitigated through deliberate actions. Such measures not only enhance food security but also benefit the local economy at no additional cost. Fig. 1 illustrates the journey of cereals from production to consumption.

Many solutions have been proposed to the global nutrition challenge, and minimizing pre- and post-harvest losses is considered the best way to solve this problem. In addition to meeting human needs, this method will also conserve resources, which can be said to establish sustainable development and all future generations will benefit from current resources.

Table 1. Comparative analysis of wheat production in 2020

Rank	**Country**	**Wheat production in thousand tons**
1	China	134.255
2	India	107.590
3	Russia	85.896
4	United States	49.691
5	Canada	35.183
6	France	30.144
7	Pakistan	25.248
8	Ukraine	24.912
9	Germany	22.172
10	Türkiye*	20.500
11	Argentina	19.777
12	Iran	15.000
22	Iraq*	6238
25	Afghanistan*	5185
42	Turkmenistan*	1320
45	Azerbaijan*	1819
76	Armenia*	132

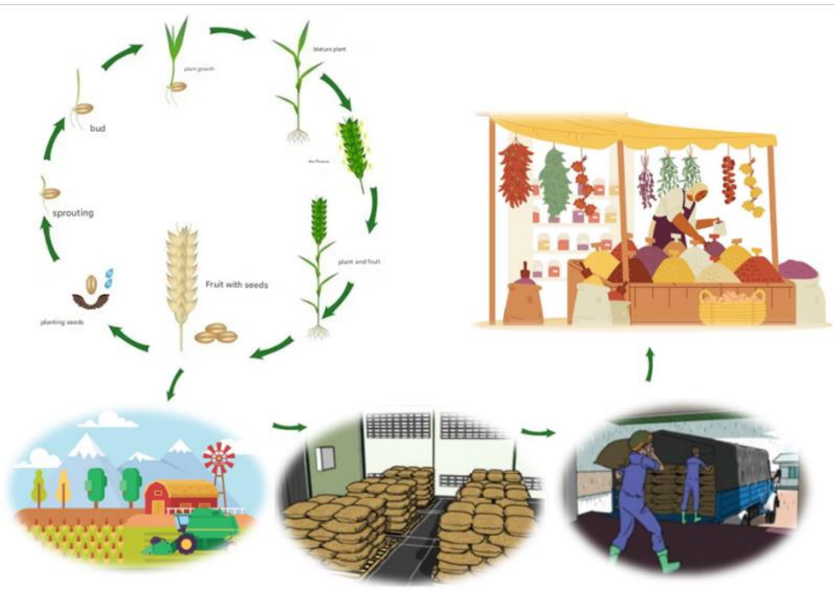

Fig. 1. The chain of grain production to consumption

2. Method

This review article is crafted through a meticulous and systematic exploration of the intricate factors contributing to wheat losses across the supply chain. To unravel the complexities of pre-harvest, harvest, and post-harvest losses, we embarked on a journey through a vast landscape of scholarly articles, technical reports, and real-world case studies. Our quest began with a deep dive into databases such as Scopus, Web of Science, and Google Scholar, where we sifted through hundreds of peer-reviewed publications, focusing on studies published between 2000 and 2024. Keywords like "wheat losses," "mechanized harvesting," "post-harvest storage," and "sustainable agriculture" guided our search, ensuring a comprehensive collection of relevant literature. We also consulted reports from authoritative organizations like the Food and Agriculture Organization (FAO) and the World Bank to ground our analysis in globally recognized data.

The heart of this review lies in its comparative approach, where we juxtapose the challenges and solutions in developed and developing countries. By analyzing case studies from regions like Iran, India, and sub-Saharan Africa, alongside examples from the United States and Europe, we uncovered striking contrasts in loss patterns and management practices. For instance, while mechanized harvesting has revolutionized wheat production in developed nations, many developing countries still grapple with outdated equipment and inadequate infrastructure. To bring these insights to life, we incorporated data on wheat production, loss rates, and technological adoption, ensuring our findings are both data-driven and contextually relevant.

In addition to the literature, we examined the role of modern technologies in mitigating losses. From advanced combine harvesters to solar dryers and biodegradable packaging, we evaluated the effectiveness of these innovations in reducing both quantitative and qualitative losses. Our analysis also highlights the interplay of environmental factors such as temperature, humidity, and weather conditions, which significantly influence wheat quality and quantity during storage and transportation. By weaving together these diverse strands of information, this review not only identifies the root causes of wheat losses but also offers practical, evidence-based solutions to address them. Through this rigorous and engaging methodology, we aim to provide a roadmap for reducing wheat losses, enhancing food security, and promoting sustainable agricultural practices worldwide.

2.1. Pre-Harvest Losses

Pre-harvest losses are caused by biological and environmental factors, mainly caused by insects, pests, and diseases. Extreme environmental events such as drought, floods, and storms can lead to significant pre-harvest losses (Habiba et al., 2015).

High-yielding varieties can increase productivity; however, they may be more prone to breakage, potentially leading to post-harvest losses (John et al., 2014). Genetic engineering has significant potential to reduce losses and prevent or reduce vulnerability to mycotoxin contamination (Kiaya et al., 2014).

2.1.1. Losses Due to Excessive Seed Use

Farmers often plant slightly more seeds than the recommended amount to ensure they achieve the desired yield and minimize economic losses from poor seed germination and low seed vigor. Typically, about 120 to 140 kg of seed is needed for wheat cultivation. However, to be cautious, farmers sometimes use as much as 300 kg per hectare. Recent research has shown that higher seed density does not always result in higher yields, and the optimal seed density can vary based on climatic and geographical conditions (Kühling et al., 2017).

Farmers need to sow seeds within a specified time frame. However, due to busy schedules or unexpected rain forecasts, some farmers use spreaders and then follow up with a disc tiller. This can lead to wheat seeds being planted at suboptimal depths, which significantly affects their ability to germinate and grow (Mohan et al., 2013).

After harvesting wheat, planting a high-demand crop like corn can negatively impact soil fertility (Yang et al., 2020). Corn production can harm soil health, primarily by depleting essential nutrients such as carbon, nitrogen, phosphorus, potassium, and calcium, which corn plants require in large quantities (Fujisao et al., 2020). Additionally, the excessive use of pesticides and herbicides in wheat farming can harm overall soil health and productivity (Rahimzadeh et al., 2011). Tillage practices associated with corn cultivation can also adversely affect soil structure, water retention, and overall fertility (Lal, 2005).

In general, soil quality is vital for ensuring agricultural productivity and preserving environmental health and biodiversity (Kalia & Gosal, 2011). The quality of food products is closely linked to soil health (Oliver & Gregory, 2015). A lack of diverse crop rotations forces farmers to rely heavily on fertilizers to maintain high productivity. The use of nitrogen fertilizers in annual row crops can lead to nitrate leaching into groundwater, posing potential health risks (Ju et al., 2006).

To reduce seed usage and optimize crop growth, several effective strategies can be implemented. These include improving planting methods, using high-quality seeds, practicing proper soil management and crop rotation, educating and raising awareness among farmers, minimizing seed waste, and consistently monitoring and evaluating performance. Farmers should adhere to scientific and environmental recommendations, as utilizing precision machinery and improved seed varieties can significantly enhance crop production and yield. Additionally, education and the organization of workshops play a crucial role in promoting awareness and the efficient use of seeds. By adopting these solutions, farmers can conserve seeds and reduce agricultural costs. Implementing crop rotation and sustainable soil management practices also contributes to maintaining soil health and protecting the environment. Through continuous farm monitoring and performance evaluation, farmers can achieve greater productivity and improvement. These measures not only help conserve natural resources and lower costs but also lead to increased production and improved product quality.

2.1.2. Losses Due to Weeds and Pests

Plant pests and weeds can significantly negatively affect crop production, threaten human health and the environment, and increase costs. Globally, crop productivity is reduced by 20 to 40 percent due to yield losses caused by pathogens, animals, and weeds (Oerke, 2006). The rate of wheat losses due to pests has been reported to range from about 14 % to over 35 percent depending on geographical location (Oerke & Dehne, 2004). Pests and weeds can cause significant damage to crops, resulting in reduced yield and reduced wheat quality (Oerke, 2006). The presence of weeds will inhibit seed growth and affect the quality and quantity of the crop. The use of pesticides and herbicides, in addition to increasing production costs, hurts human health. To reduce the damage caused by pests and weeds, very sustainable agricultural practices are used. Some of these practices include crop rotation to prevent pest accumulation, use of pest and disease-resistant seeds, enriching the soil with organic fertilizers instead of chemical fertilizers, and using biological control methods such as releasing natural enemies of pests. Also, optimal irrigation and proper water management can help reduce the growth of weeds. Education and awareness of farmers about sustainable practices will also play an important role in reducing losses.

2.2. Harvesting Losses

Harvesting is the process of collecting ripe grains from the field, and its efficiency significantly impacts crop losses. In less developed countries, harvesting is often done manually using tools like sickles, which, despite being more precise, can lead to delays or missed harvests due to labor shortages. In contrast, developed countries rely heavily on mechanized harvesting, which, while efficient, can still result in grain losses if not properly managed (Nath et al., 2017). The timing of harvesting is critical: harvesting too late can cause grains to break and fall due to drying wheat ears, while harvesting too early can reduce yield and quality due to high moisture content, leading to increased rotting and reduced storability (Turner et al., 2021; Ronga et al., 2020; Alt et al., 2019).

Mechanized harvesting, particularly using combine harvesters, has become a practical solution for minimizing losses and improving productivity. Combines reduce production costs, enhance labor efficiency, and decrease losses from unharvested crops. However, improper adjustments or high operating speeds can lead to grain losses, with natural loss rates typically up to 7%. These losses can be reduced to around 3% by optimizing forward speed and machine settings, though this may not always be cost-effective (Fu et al., 2018; Ghaziani et al., 2023). Key components of the combine, such as the threshing drum, play a vital role in minimizing losses. Adjusting parameters like drum rotation speed and distance can improve threshing performance and reduce grain breakage (Manzoor et al., 2021). Recent research highlights that grain losses increase with higher operating speeds, with optimal settings being a forward speed of 4 km/h and a head speed of 25 rpm (Mokhtar et al., 2020; Ghaziani et al., 2023).

The highest losses in combines often occur at the cutting platform, influenced by factors such as inappropriate wheel and flywheel speeds, blade breakage, and misalignment (Safari & Rostami, 2023). Studies comparing combine models, such as the John Deere 955 and Class, show that threshing combines significantly reduce loss rates compared to conventional methods, especially at varying moisture levels (Agheleshkhani, 2017). Additionally, adjusting the threshing drum diameter can improve separation capacity and material distribution, further minimizing grain breakage (Manzoor et al., 2021). On sloped lands, hill combines that maintain level threshing drums can achieve uniform distribution and reduce losses. Regular technical maintenance and inspections are essential for maximizing efficiency and minimizing losses.

Weather conditions during harvest also play a critical role. Unexpected rain can promote mold growth and increase the risk of aflatoxin or mycotoxin contamination, while inadequate water supply before harvest can cause wheat ears to dry out and be damaged by wind (Raut et al., 2018). Proper land leveling before planting is crucial to ensure even water distribution and prevent losses during critical growth periods. Uneven land can lead to some plants drying out due to insufficient water, further exacerbating harvest losses. By addressing these factors—timely harvesting, proper machinery adjustments, regular maintenance, and land preparation—farmers can significantly reduce losses and improve both yield and quality.

2.2.1. Threshing Losses

Threshing is the process of separating grains from straw, stalks, and ears, and its efficiency significantly impacts grain loss and quality. In developing or less developed countries, threshing is often done manually using methods such as rubbing with rubber tools or beating the plants. While these techniques are labor-intensive, they are still widely used due to limited access to advanced machinery (Nath et al., 2021; Lad et al., 2020). In contrast, industrialized countries rely on combine harvesters, which integrate harvesting, threshing, and cleaning into a single operation, significantly improving efficiency and reducing labor requirements (Shah, 2013).

The method and timing of threshing are critical factors influencing grain loss. Losses during threshing can occur due to grain scattering, seed shedding, insufficient separation of grain from straw, and grain breakage caused by excessive force (Hossain et al., 2023). Moisture content is another key factor: high humidity can lead to grain crushing and reduced quality, while excessively low moisture levels increase the risk of grain breakage. Proper management of moisture levels is therefore essential to minimize losses and maintain grain quality. Additionally, the volume of material fed into the threshing machine must be carefully controlled, as it directly affects separation efficiency and breakage rates. Overloading the machine can lead to incomplete separation and higher losses, while underloading may reduce productivity.

To optimize threshing efficiency, it is crucial to balance these factors—moisture content, material volume, and threshing force—especially when using mechanized systems like combine harvesters. In manual threshing, attention to technique and timing can help reduce losses, while in mechanized systems, proper machine calibration and operation are key. By addressing these variables, farmers can significantly reduce threshing losses, improve grain quality, and enhance overall productivity.

2.2.2. Genetic Diversity

Some plant species are inherently more susceptible to losses than others, for example, wheat, corn, and barley have lower losses than rice. Hybrid varieties experience higher loss levels than inbred varieties due to more grains in the cluster because the clusters are heavier due to the greater load, and at harvest time when the moisture level is low, we will see stem breakage due to wind currents or vibrations caused by harvesting (Kiaya, 2014).

2.3. Postharvest Losses (PHL)

encompass both physical and nutritional losses, with contamination and poor management being the most significant contributing factors (Kiaya, 2014). These losses can be categorized into two main types: quantitative losses, which refer to reductions in weight or volume, and qualitative losses, which involve changes in appearance, marketability, and nutritional value. Both types of losses are particularly prevalent in developing countries, where infrastructure and management practices are often less advanced (Lipinski et al., 2013).

The primary causes of postharvest losses include the type of crop, prevailing seasons, and climatic, genetic, and environmental factors (Moriarty, 2013). For instance, certain crops are more susceptible to spoilage or damage based on their inherent characteristics, while environmental conditions such as humidity, temperature, and pests can exacerbate losses. Qualitative losses are equally, if not more, critical than quantitative losses because they directly impact the producer's income. A decline in quality not only reduces the selling price but can also render the product unmarketable, leading to financial losses that may exceed those caused by quantity reductions. Addressing postharvest losses requires a focus on improving management practices, reducing contamination, and adapting to environmental and climatic challenges. By prioritizing both quantitative and qualitative aspects, producers can minimize losses, enhance marketability, and secure better financial outcomes.

2.3.1. Weather Conditions

Weather conditions, including temperature, humidity, and rainfall intensity, significantly influence post-harvest activities (Bendito & Twomlow, 2015). Rainfall, while beneficial during crop growth, can increase losses during harvest. High moisture content in crops at harvest or in storage creates ideal conditions for germination and microbial growth, emphasizing the need for dry storage environments with relative humidity below 70% to prevent mold (Afzal et al., 2019). Effective measures to mitigate weather-related losses are essential for preserving crop quality.

2.3.2. Grain Maturation and Post-Harvest Operations

The maturity and ripening of crops affect the rate of post-harvest losses. Each type of crop has a specific life cycle that depends on the characteristics of the seed and the weather conditions of the region. Moisture and pigment content are useful for determining the timing of post-harvest operations, drying, storage, etc., and help reduce losses. Achieving optimal maturity can significantly reduce losses (Arah et al., 2015). However, the timing of grain harvest is highly influenced by market demand and storage facility availability. Sometimes, farmers harvest their crops before they reach full maturity due to financial constraints or market demand (selling at higher rates). This practice leads to a decrease in the nutritional and economic value of the crops. Ultimately, farmers decide when and how to harvest the crop to maximize profits and minimize losses. The extent of variation in losses depends on the choices made by farmers.

2.3.3. Losses Due to Transportation

Transportation is essential for transporting grains from the farm to the market. The movements made are considered one of the main causes of losses (Kumar & Kalita, 2017). In developing countries, loading and unloading of trucks is done by labor, which will cause losses and increase the cost of production. While in developed countries, all stages are done by tools and machinery.

In addition, the type and material of bags used for storing and transporting grains play an important role in minimizing losses. Poor quality of bags will cause grain to fall at each stage (Riaz et al., 2017). In a study, the rate of losses due to transportation was reported to be 2 to 10 % (Nath, 2017). Traditional methods of transportation and loading often result in high PHL, as the seeds are poorly protected from contamination, pests, and birds. There is also evidence of breakage and quality loss.

2.3.4. Drying Losses

Drying is a crucial and challenging step in the cereal production process, as it involves reducing the moisture content of the grain for safe storage. The drying process can significantly impact the quality of the final product (Maciel

Table 2. Moisture safe for storage

ge period	(%) Moisture content required for safe storage	Potential p
3 weeks	14-18	Mold, disc
months8	12-13	Insect da
han 1 year	Maximum 9	Loss of

et al., 2015). The amount of loss during drying depends on several factors, including the chosen method and equipment. Drying methods can be either natural (like sun or shade drying) or mechanical (using dryers) (Kumar & Kalita, 2017). For wheat, drying losses typically range from 1.56 to 5% (Maciel et al., 2015). When grains are spread out in open areas for sun drying, they become vulnerable to consumption by birds and insects. Additionally, they may get contaminated with foreign materials such as stones, dust, and other debris (Oguntade et al., 2014).

Moreover, the drying process is influenced by moisture levels and can lead to significant losses, as illustrated in Table 2 (Nath et al., 2024). Overdrying can cause the kernels to crack, damaging the embryo coat and negatively affecting their marketability.

In contrast, the use of modern drying methods has several advantages over natural drying. These include reduced transport losses, increased control over hot air temperatures, and more efficient use of space. However, there are challenges such as high initial and maintenance costs and lack of operational knowledge to develop the use of modern dryers. Solar dryers have a simple and low-cost design that is suitable for small scale. Solar dryers have potential use in regions with hot, arid, or semi-arid climates (Abdoli et al., 2017). In industrialized countries, technologies such as NIR-based dryers, microwave dryers, and hot air convection dryers are used, which have a high initial cost; but ensure product quality and value (Fleurat-Lessard, 2017). In modern dryers, the drying and humidification process is carried out uniformly, which affects marketability, and also the possibility of mold growth, germination, and insects is minimized. Using solar dryers minimizes drying costs and also has no pollution or environmental impact.

2.3.5. Storage Losses

Several factors contribute to the decline in grain quality and quantity during storage, with temperature and humidity being the most significant. These elements affect important traits such as seed germination, milling quality, and commercial value. For instance, ambient temperatures between 20 and 40°C, combined with relative humidity above 70%, can promote the infestation of storage pests like the proboscis, small grain borer, and chepara beetle (Tefera et al., 2016). In many less-developed countries, traditional storage methods are still in use. The lack of basic post-harvest infrastructure in these regions is a major factor contributing to post-harvest losses (PHL) (Omotajo et al., 2018). Financial, management and technological constraints hinder the development of better infrastructure. As a result, significant losses often occur in the field (Kiaya, 2014). In these countries, PHL rates for cereals can reach around 10–15% (Tadesse Dessalegn et al., 2017). Research indicates that high-income countries tend to experience greater volumes of grain waste at the consumption level (Sawaya, 2017), while low-income regions face the opposite issue (Khodkam & Najafi, 2021).

Storage structures are crucial for keeping agricultural products safe. In many developing countries, minimal infrastructure and cost-effective storage facilities are commonly used (Razavizadeh et al., 2023). Expanded metal silos have become quite popular because they eliminate insect losses. These silos are suitable for small-scale storage and are affordable (Zufiaurre et al., 2019). A good storage system should effectively reduce PHL. Losses in this area often stem from inefficient storage infrastructure. By designing an effective system, losses can be minimized by up to 98% (Donate et al., 2015). Grain moisture levels play a crucial role in reducing storage losses. Agricultural products must be dried before storage to prevent spoilage. In Iran, a significant concern for farmers is the lack of adequate storage facilities and silos, which poses a major challenge in the storage sector. As a result, farmers often have to store their products under unsafe conditions, leading to substantial losses each year.

In developed countries, advanced technologies and methods are commonly used, resulting in a significant reduction in post-harvest losses (PHL) from the farm to the consumer (Kumar & Kalita, 2017). However, post-harvest losses at the consumption stage in these countries are higher than in less developed countries (van Gogh et al., 2017). This can be attributed to a preference for convenience and comfort, which drives these losses. In Iran, many storage facilities are outdated or fail to meet current needs in terms of structure and technology. Additionally, the use of plain combine harvesters in sloping fields contributes significantly to increased loss rates. In these conditions, the threshing and counter-threshing processes become angled, leading to incomplete separation and a higher incidence of grain breakage. Fig. 2 shows the factors affecting post-harvest losses in grain storage.

2.3.6. Packaging Losses

Packaging plays a significant role in minimizing losses, as low-quality packaging can lead to product contamination, insect infiltration, and a decrease in commercial value.

Fig. 2. Factors affecting post-harvest losses in grain storage

Common packaging materials include woven poly bags, high-density polyethylene paper bags, and other plastics. Recently, biodegradable packaging materials, such as those made from sugarcane-derived plastics, have been recommended (Sani et al., 2021). This approach is beneficial for both the environment and the economy, as it utilizes sugarcane waste to produce these materials. Innovative packaging solutions can help reduce post-harvest losses (PHL). Biodegradable and nanocellulose-based packaging are environmentally friendly options that not only help prevent food losses but also extend the shelf life of products (Ajwani-Ramchandani et al., 2021). These advancements reflect a commitment to sustainability and the smart use of materials, where waste is repurposed and recycled.

The raw materials for producing biodegradable packaging often come from waste products that pose risks to human and animal ecosystems. This method not only lowers production costs but also addresses waste disposal issues, as these materials pose no risk when disposed of after use. While it may not be possible to eliminate all losses, achieving a 50% reduction is feasible and would be highly beneficial (van Gogh et al., 2017).

3. Conclusions

This review underscores the critical importance of addressing wheat losses as a cornerstone for achieving global food security and sustainability. Wheat, a staple crop that feeds billions, faces significant quantitative and qualitative losses at every stage of the supply chain, from pre-harvest to post-harvest. These losses are driven by a multitude of factors, including pests, diseases, inefficient harvesting techniques, inadequate storage infrastructure, and environmental challenges such as temperature and humidity fluctuations. In developing countries, the lack of access to modern technologies and infrastructure exacerbates losses, particularly at the farm level, where outdated practices and limited resources prevail. In contrast, developed nations experience higher losses during the consumption phase, often due to inefficiencies in distribution systems and consumer behavior. By addressing these challenges through targeted interventions, we can unlock substantial opportunities to increase food availability without expanding agricultural land or depleting natural resources, thereby contributing to a more sustainable and resilient food system.

The adoption of advanced technologies and innovative practices has demonstrated remarkable potential in reducing wheat losses. Mechanized harvesting, when combined with precise adjustments and regular maintenance, can significantly minimize grain shedding and breakage, ensuring higher yields and better-quality grains. Modern storage solutions, such as expanded metal silos and controlled-environment systems, can prevent spoilage and pest infestations, while solar-powered drying methods offer sustainable alternatives to traditional practices. Additionally, the use of biodegradable packaging materials and integrated pest management strategies not only reduces losses but also aligns with global efforts to promote environmental sustainability. Pre-harvest interventions, including the cultivation of high-yielding and pest-resistant seed varieties, optimized planting practices, and improved soil health management, can further mitigate losses at the source. These strategies, when combined with enhanced farmer education and access to resources, can create a more resilient and efficient wheat supply chain, capable of meeting the growing demands of a rapidly expanding global population.

In conclusion, reducing wheat losses is not merely a technical challenge but a global imperative that requires collaboration across sectors, regions, and disciplines. Policymakers, researchers, agricultural stakeholders, and farmers must work together to implement evidence-based solutions tailored to local contexts. By prioritizing the reduction of both quantitative and qualitative losses, we can ensure that the benefits of increased food availability are equitably distributed, particularly in regions most vulnerable to food insecurity. This review serves as a comprehensive roadmap for action, emphasizing that the path to a sustainable future lies in minimizing waste, optimizing resources, and fostering innovation at every stage of the wheat supply chain. Through collective effort and a commitment to sustainable

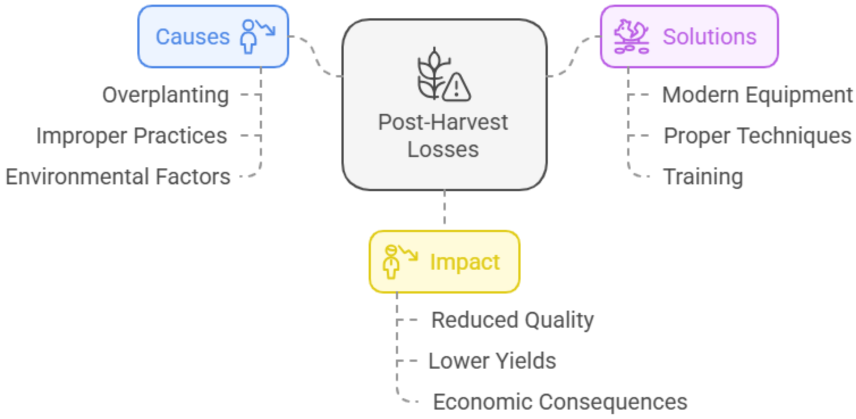

Fig. 3. Addressing Post-Harvest Losses in Wheat Production

practices, we can transform the challenge of wheat losses into an opportunity for global food security, economic stability, and environmental stewardship. The time to act is now, as the stakes are high, and the rewards—ensuring a food-secure future for generations to come—are immeasurable.

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