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Economic importance of wheat (*Triticum aestivum* L.) and current advances in wheat genome biotechnology

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ABSTRACT

Wheat (*Triticum aestivum* L.) is one of the most economically significant crops worldwide, serving as a staple food for billions of people and a key contributor to global agricultural GDP. This study explores the economic importance of wheat and the current advancements in wheat genome biotechnology, focusing on recent developments that enhance wheat productivity, disease resistance, and nutritional value. The research employs asystematic review methodology, analyzing peer-reviewed literature, reports, and scientific articles to evaluate the role of wheat in global food security and technological innovations in wheat breeding.Key findings highlight wheat's contribution to various industries, including food production, biofuels, and livestock feed, while also addressing its role in global trade. Advances in genome sequencing, CRISPR-Cas9 gene editing, marker-assisted selection, hybrid wheat breeding, and synthetic wheat development have revolutionized wheat genetics, leading to higher yields and resilience against climate change and diseases. However, challenges such as complex genome structures, regulatory barriers, and limited access to genomic technology in developing nations persist. The study concludes that while wheat genome biotechnology holds great promise for future food security, increased investment, international collaboration, and public awareness are crucial for its successful adoption. Recommendations emphasize the need for sustained research funding, capacity building, and policy reforms to bridge the gap between technological advancements and practical agricultural applications.

Keywords: Disease resistance; CRISPR-Cas technology; Wheat; Genome engineering; Climate change

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Introduction

Wheat (*Triticum aestivum*) is one of the most important cereal crops cultivated worldwide, serving as a staple food with beneficial dietary (nutritional), vitamins, phytochemicals, and mineral componentsfor more than 35% of the world's populationi.e., providing nourishment to billions of people (FAO, 2021). It is a fundamental component of global food securityas it is the second most cultivated cereal crop (globally), that accounts for approximately 20% of the world's total dietary calories and protein intake (FAO, 2021).

Wheat is cultivated across diverse agro-climatic zones, and it has been integral to the development of human civilizations due to its adaptability, high caloric value, and broad utility in food production (Shewryand Hey, 2015). It is a major source of essential nutrients, providing carbohydrates, proteins, vitamins, and minerals that contribute to balanced human nutrition (Singh *et al.*, 2020). Beyond its nutritional value, wheat plays a critical role in national and global economies, supporting the livelihoods of millions of farmers, agricultural-based processing industries, and other stakeholders in the agricultural value chain (Curtis and Halford, 2014).

Despite its significance, wheat production has faced numerous challenges over time. Historically, productivity has been constrained by biotic and abiotic factors, including pests, diseases, drought, and extreme temperatures

(Chen *et al.,* 2017). Global climate change also exacerbated these challenges, leading to reduced yields or production outputin many regions, particularly in areas prone to heat stress and water scarcity (Lesk *et al.,* 2016). Soil degradation and declining arable land due to urbanization and unsustainable farming practices have further limited the ability of farmers to meet the growing demand for wheat (FAO, 2021). Wheat production faces numerous challenges that threaten global food security and economic stability. Climate change, characterized by rising temperatures, erratic rainfall, and the emergence of new pests and diseases, has significantly impacted wheat yields in many regions (Porter *et al.,* 2014). These environmental changes have led to crop failures and reduced productivity, particularly in regions highly dependent on wheat as a staple crop. Additionally, population growth and urbanization have steadily increased the demand for wheat-based products, placing pressure on existing production systems to meet food and industrial needs (Godfray *et al.,* 2010).

Various approaches have been adopted to mitigate these challenges. Traditional breeding techniques have been instrumental in developing wheat varieties with improved resistance to diseases and environmental stresses (Gupta *et al.,* 2020). The Green Revolution of the 20th Century brought significant advancements in wheat production based on the following rationale: the cultivation of high-yielding varieties to improve yield, the use of fertilizers, and irrigation systems which resulted in increased food production and reduced hunger in many regions (Pingali, 2012). However, these approaches had limitations, including reliance on chemical inputs, loss of genetic diversity, and environmental degradation (Kumari and Sharma, 2021 and Tilman *et al.,* 2011). Moreover, the adoption of biotechnological advancements in wheat improvement is often hindered by regulatory constraints, ethical concerns, and limited access to resources in developing countries. While genomic technologies such as CRISPR-Cas9 and marker-assisted selection (MAS) have immense potential to improve yield biotechnology, disparities in access to these technologies create inequalities among stakeholders, leaving smallholder farmers at a disadvantage (Gocal *et al.,* 2019). The ethical debates surrounding genetically modified organisms (GMOs) also pose challenges to the widespread acceptance and implementation of biotechnological innovations in wheat improvement.

The use of modern biotechnological techniqueshas emerged as transformative tools in wheat production. The sequencing of the wheat genome, completed in 2018 by the International Wheat Genome Sequencing Consortium (IWGSC), provided critical insights into the genetic basis of traits such as disease resistance, drought tolerance, and grain quality (IWGSC, 2018). Marker-assisted selection (MAS), genetic modification (GM), and genome editing tools like CRISPR-Cas9 have enabled researchers to develop wheat varieties that are more resilient, productive, and nutritious (Kumari et al., 2022a and Zhang *et al.,* 2022). Current advances in wheat genome technology represent a significant step toward sustainable agricultural practices. These innovations aim to address the challenges posed by climate change, growing populations, and limited natural resources, ensuring that wheat production can meet the needs of future generations (Kumar *et al.,* 2021). However, despite the promise of genome biotechnology, challenges such as high costs, regulatory hurdles, and public acceptance remain key obstacles to its widespread adoption (Chen *et al.,* 2020). Therefore, this study was set up to analyze the economic importance of wheat, the past and present challenges in wheat production, and the transformative role of wheat genome biotechnology. Furthermore, the current review project will explore thehistorical trends, efforts, the limitations of traditional approaches, and the potential of genomic technologies as a way forward for sustainable wheat production worldwide. The economic importance of wheat and how advancements in genome biotechnology can provide sustainable solutions for improving wheat productivity, resilience, and quality. By focusing on genomic strategies, this study emphasizes the role of science and technology in overcoming the barriers to food security and agricultural sustainability.

2.0 Nutrient analysisof wheat grain

Wheat is a nutritionally rich cereal crop, containing a variety of essential macronutrients, minerals, vitamins, and phytochemicals. These components contribute to its role as a staple food and a key source of energy and nutrition globally. The nutritional composition of wheat varies depending on its species, variety, growing conditions, and processing methods. Understanding these components provides insights into wheat's economic importance and its contributions to human health.

2.0.1 Proximate composition of wheat

The proximate composition of wheat refers to its major nutritional components, including moisture (10-14%), protein (10-15%), carbohydrate (60-70%) etc., as shown in Table 1. Wheat grains are particularly high in carbohydrates, provide energy, and contain moderate amounts of protein and dietary fiber, making them essential for balanced diets (Shewry, 2009).

Table 1. Proximate Analysis of Wheat (Values per 100g of Wheat)

Component	*Composition*	
	Minimum Value (%)	**Maximum Value (%)**
Moisture	10	14
Protein	10	15
Carbohydrate	60	70
Fat	01	03
Crude fiber	02	03
Ash (Minerals)	01	02

2.0.2 Mineral composition of wheat

Wheat contains a variety of essential minerals that are vital for human health, including potassium (≤400 mg/100g), phosphorus (≤350 mg/100g), magnesium (≤150 mg/100g), calcium (≤30 mg/100g), iron (≤4 mg/100g), and zinc (≤3 mg/100g) as shown (Table 2) below. These minerals contribute to key physiological processes, such as bone health, energy metabolism, and immune function. The mineral content in wheat depends on soil conditions, wheat variety, and post-harvest processing (Oury *et al*., 2006)

Table 2. Mineral Composition of Wheat (values per 100g of Wheat Grain)

Minerals	*Concentration*	
	Minimum (mg/100g)	**Maximum (mg/100g)**
Potassium (K)	300	400
Phosphorus (P)	250	350
Magnesium (Mg)	100	150
Calcium (Ca)	20	30
Iron (Fe)	02	04
Zinc (Zn)	02	03

2.0.3 Phytochemical composition of wheat

Wheat grains are rich in bioactive phytochemicals, including phenolic acids (≤30 mg/100g), flavonoids (≤10 mg/100g), lignans (≤5 mg/100g), and alkylresorcinols (≤25 mg/100g) as shown (Table 3). These compounds have antioxidants, anti-inflammatory, and anticancer properties, making wheat a functional food with health benefits. Phytochemicals are primarily concentrated in the bran and germ layers of wheat grains, which are often removed during milling (Adom and Liu, 2002).

Table 3. General Phytochemical Composition of Wheat

Phytochemical	*Concentration*	
	Minimum (mg/100g)	**Maximum (mg/100g)**
Phenolic acids	20	30
Flavoniods	5	10
Alkylresorcinois	15	25
Lignans	02	05
Saponins	01	02

2.0.4 Vitamin composition of wheat

Wheat contains essential vitamins, particularly B-complex vitamins such as thiamine (≤0.60 mg/100g), riboflavin (≤0.20 mg/100g), niacin (≤6.00 mg/100g), and folate (≤0.05 mg/100g) as shown (Table 4). These vitamins play crucial roles in energy metabolism, nervous system function, and red blood cell formation. Wheat is also a source of vitamin E, a powerful antioxidant, primarily found in the germ (Hussain *et al*., 2010).

Table 4.Vitamin Composition of Wheat

Vitamins	*Concentration*	
	Minimum (mg/100g)	**Maximum (mg/100g)**
Thiamine (B1)	0.40	0.60
Riboflavin (B2)	0.10	0.20
Niacin (B3)	4.00	6.00
Folate (B9)	0.02	0.05
Vitamin E	1.00	2.00

3.0 Economic Importance of Wheat

Wheat (*Triticum spp.*) is one of the most economically significant cereal crops globally, contributing substantially to food security, industrial applications, and international trade. It serves as a staple food for billions of people, forming the basis of diets in many regions, particularly in North America, Europe, Asia, and parts of Africa (Kumari et al., 2022b and

FAO, 2021). The economic importance of wheat extends beyond agriculture, influencing industries such as food processing, livestock feed production, and biofuel manufacturing. (FAO, 2021)

Wheat in the United States Economy

The United States is one of the world's largest producers and consumers of wheat, with the crop contributing significantly to its agricultural sector.

Contribution to GDP and Employment

- Wheat production in the U.S. generates billions of dollars annually, supporting rural economies and providing jobs in farming, milling, transportation, and food manufacturing.
- According to the U.S. Department of Agriculture (USDA), wheat contributed approximately $10 billion to the U.S. economy in 2022 (USDA, 2022).
- The wheat industry directly and indirectly supports millions of jobs, including farmers, agronomists, millers, bakers, and export traders. (USDA, 2022)

Well Wheat remains one of the most economically important crops globally,
contributing to national GDPs, employment, and international trade. The U.S., as a top producer and exporter, benefits significantly from wheat production, both domestically and in foreign trade. On a global scale, wheat supports food security and economic stability, making it a vital commodity for many nations. Its importance is expected to grow as demand for wheat-based products increases, particularly in developing countries.

3.0.1 Contribution to Global Economy and Trade

Wheat is a key agricultural commodity with annual global production exceeding 775 million metric tons as of 2021 (Table 5 and Fig 1), making it the second most-produced cereal after maize (FAO, 2021). Major wheat-exporting nations such as the United States, Canada, Russia, Australia, and the European Union generate billions of dollars in revenue from wheat trade. The global wheat market is estimated at over $50 billion, influencing economic stability in producing countries (USDA, 2022).

3.0.2 Role in Employment and Livelihoods

Wheat farming provides employment opportunities across the value chain, from cultivation and harvesting to processing and marketing. Millions of small-scale farmers depend on wheat cultivation for their livelihoods, particularly in developing nations. Additionally, industries such as milling, baking, and food processing create millions of jobs worldwide (Sharma *et al.,* 2020).

3.0.3 Industrial Applications

Beyond human consumption, wheat is a key ingredient in various industries. It is processed into:

- Flour: Used in baking bread, pasta, and confectionery.
- Bioethanol Production: Wheat-based biofuels contribute to the renewable energy sector.
- Livestock Feed: Wheat bran and by-products are an important animal feed source.
- Pharmaceuticals and Cosmetics: Wheat derivatives are used in medicinal formulations and skincare products (Shewryand Hey, 2015).

3.0.4 Food Security and Price Volatility

The price of wheat directly affects global food security. Fluctuations in wheat production due to climate change, political conflicts, and economic instability can lead to significant price variations, impacting vulnerable populations. For instance, the Russia-Ukraine war in 2022 disrupted global wheat supply chains, leading to price surges and food shortages in many import-dependent countries (OECD, 2022).

Table 5.The economic contribution of wheat global agricultural GDP

Country	Annual Production (metric tons)	Contribution (%)	Importance
China	136.0	15%	Food, animal feed, biofuels
India	110.0	14%	Food security, flour production
Russia	92.0	18%	Export, animal feed
United states	44.0	12%	Baking industry, ethanol, export
European union	134.0	16%	Pasta, bakery, feed industry
Canada	35.0	10%	Bread, beer brewing, exports
Australia	32.0	11%	Export, livestock feed
Argentina	19.5	8%	Domestic consumption, export
Brazil	6.0	6%	Flour milling, pasta production
Africa (Total)	27.5	7%	Staple food, bakery industry
Global (Total)	~800.0	~12%	Food security, trade, industry

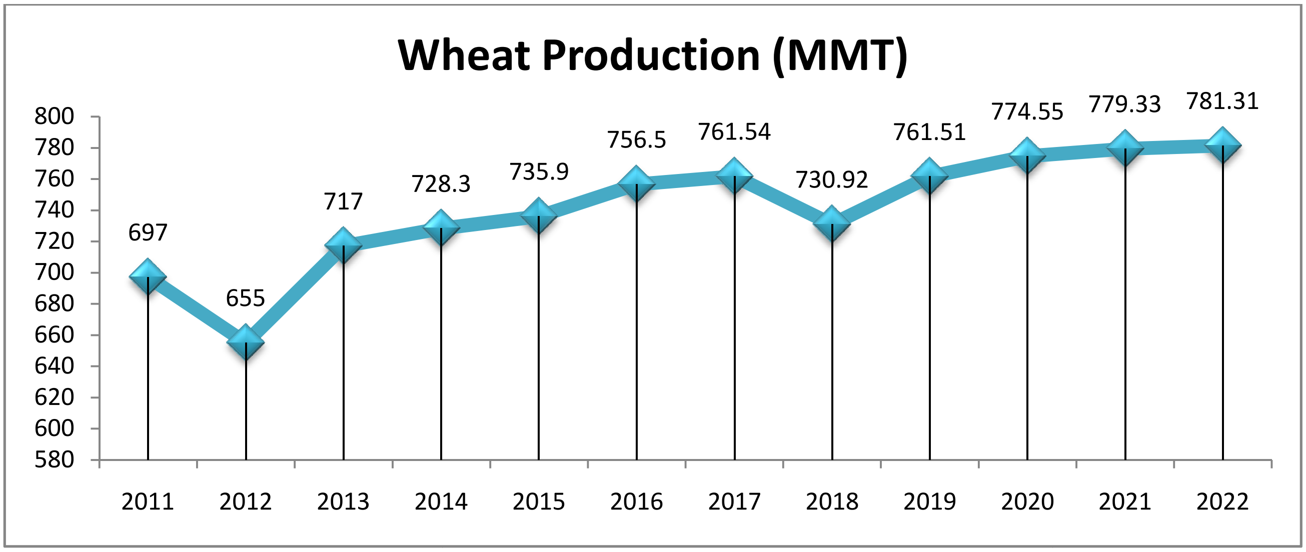

Fig1. Global wheat production trends over the last decade

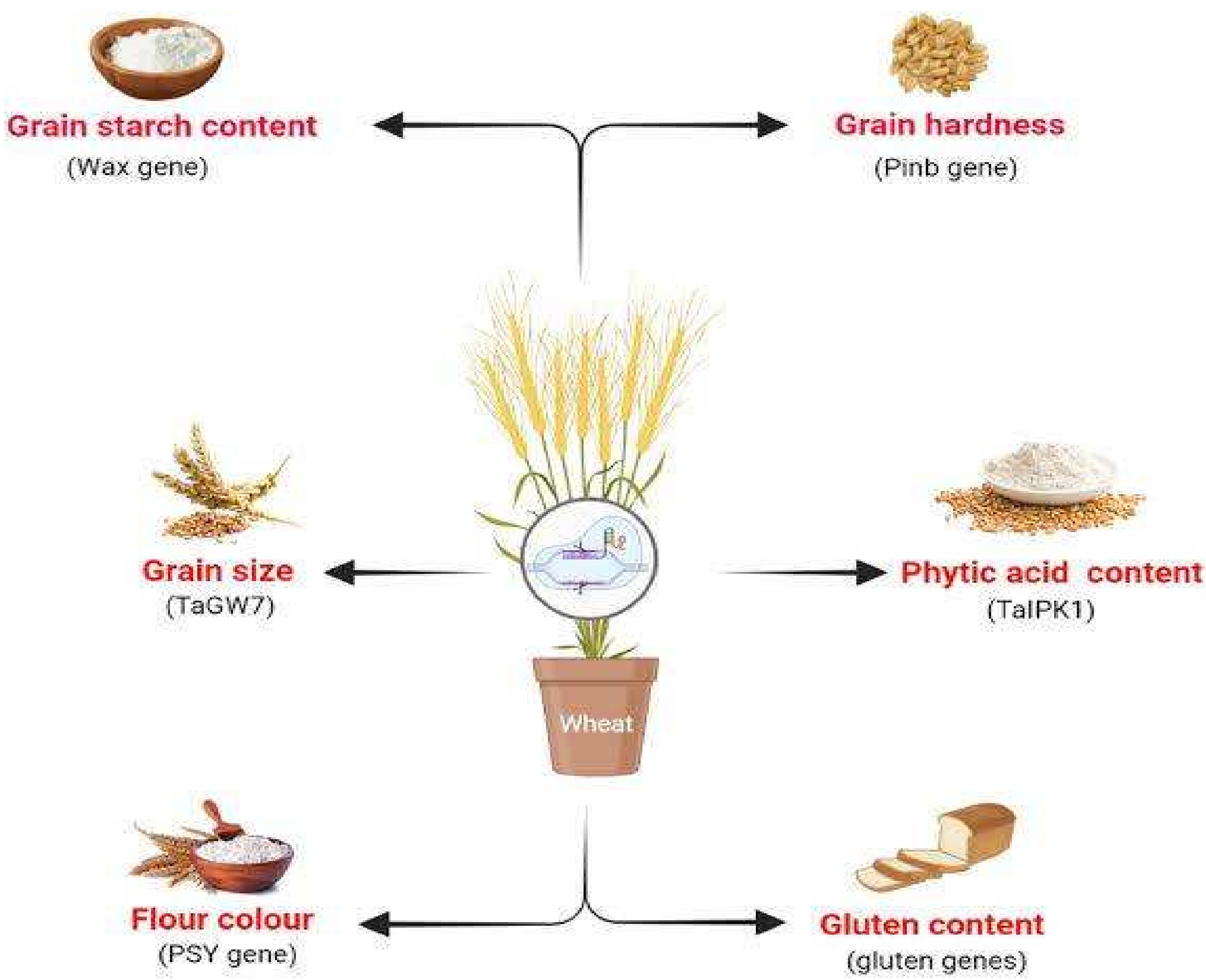

Fig 2. CRISPR-Cas9 gene-editing mechanism in wheat improvement

Table 6. Summary of current advancements in wheat genome biotechnology

Advancement	Description	Key Benefits	References
Genome Sequencing	The full sequencing of the wheat genome (2018) enabled better understanding of wheat genetics and trait selection.	Facilitates marker-assisted breeding and genetic improvements.	International Wheat Genome Sequencing Consortium (IWGSC), 2018
CRISPR-Cas9 Gene Editing	Precision genome editing is used to enhance disease resistance, drought tolerance, and nutritional content.	Produces high-yield and climate-resilient wheat varieties.	Zhang *et al.,* 2021; Wang *et al.,* 2020
Marker-Assisted Selection (MAS).	Identifying and selecting desirable traits using genetic markers for targeted breeding.	Accelerates breeding programs, improves quality and resistance	Borrill *et al.,* 2019
Hybrid Wheat Development	Creation of hybrid wheat varieties through genetic improvements.	Increases yield potential and adaptability to different environments.	Longin*et al.,* 2020
Synthetic Wheat Breeding.	Crossbreeding wild relatives with cultivated wheat to enhance genetic diversity.	Improves resistance to pests, diseases, and environmental stress	Reynolds *et al.,* 2019
RNA Interference (RNAi) Technology	Gene silencing techniques are used to control pest and disease susceptibility.	Reduces dependency on chemical pesticides.	Knox *et al.,* 2022
Biofortification.	Genetic modification and selective breeding to enhance micronutrient content (e.g., iron, zinc, and vitamin A).	Addresses global malnutrition and food security challenges	Singh *et al.,* 2021

Source: FAO (2023)

Table 7. Limitations and challenges in wheat genome technology

Limitation/challenges	Description
Complex Genome Structure	Wheat's hexaploid genome (6 sets of chromosomes) is large and complex, complicating sequencing, assembly, and gene annotation.
Incomplete Genome Annotation	Not all genes, particularly in repetitive or complex regions, are fully annotated, leaving gaps in understanding the genome's structure and function.
Limited Functional Genomics	The lack of comprehensive functional genomics tools makes it difficult to link genomic data to practical applications such as disease resistance or stress tolerance.
Access to Genetic Resources	Genetic resources, such as high-quality reference genomes or diverse varieties, are limited, hindering research on a broad range of wheat types.
Cost and Time-Intensive.	Large-scale genome sequencing and analysis require significant financial resources and time, limiting the scope of research or breeding applications
Polyploidy and Homoeologous Gene Silencing.	The redundancy of homoeologous genes in polyploid wheat can complicate the interpretation of gene function, as silencing one copy may be compensated by another
Environmental Influence on Expression	Wheat traits like yield and disease resistance are influenced by environmental conditions, making it hard to link genomic data with stable phenotypic outcomes across diverse environments.
Bioinformatics Challenges	Efficient analysis of vast genomic data requires advanced bioinformatics tools, which may not always keep up with the volume of data, limiting data interpretation and application in breeding programs.

- Wheat provides about 20% of global calories and protein intake, making it a crucial component of diets worldwide (FAO, 2022).
- Over 2.5 billion people depend on wheat as their primary source of nutrition. (FAO, 2022).
- In many developing countries, wheat is an affordable staple that helps reduce hunger and malnutrition. (FAO, 2022).

3.0.5 Industrial and Livestock Use

Wheat is used in various industries, including:

- Food processing: Wheat flour is a core ingredient in bakery products, pasta, and confectionery items.
- Ethanol and biofuel production: Wheat starch is used in the production of bioethanol.

Livestock feed: Wheat by-products like bran and middling are essential in animal feed, especially for poultry and cattle.

3.1 Current Advances in Wheat Genome Technology

Scientific advancements in wheat genome research have significantly improved wheat breeding, resilience to stress, and overall productivity. Breakthroughs include:

3.1.1 Wheat Genome Sequencing

The International Wheat Genome Sequencing Consortium (IWGSC)'s 2018 sequencing of the wheat genome was a landmark achievement, enabling precise genetic mapping for targeted breeding (Appels *et al.,* 2018). This advancement has facilitated the identification of genes responsible for yield, disease resistance, and stress tolerance.

3.1.2 CRISPR-Cas9 Gene Editing

CRISPR-Cas9 has been applied to wheat breeding for:

- Improved disease resistance (e.g., resistance to rusts and Fusarium head blight).
- Drought and heat tolerance, helping wheat adapt to climate change.

Biofortification, increasing wheat's zinc and iron content to combat malnutrition (Zhang *et al.,* 2021). A comprehensive description of the application of CRISPR-Cas technology in wheat genome engineering was shown (Fig 2)

3.1.3 Marker-Assisted Selection (MAS)

MAS enables breeders to accelerate the selection of superior traits, reducing breeding cycles and improving the efficiency of developing high-yielding wheat varieties (Kumari et al., 2024 and Collard andMackill, 2008).

3.1.4 Hybrid Wheat Development

Hybrid wheat breeding, using cytoplasmic male sterility (CMS) and chemical hybridizing agents (CHAs), has resulted in higher-yielding and more stress-resistant varieties (Longin *et al.,* 2012).

3.1.5 Synthetic Wheat and Genomic Prediction

By crossing cultivated wheat with wild relatives, researchers have enhanced genetic diversity, improving pest resistance and drought adaptation. Genomic selection uses big data to predict the best-performing wheat genotypes, reducing the time required for variety development (Trethowan and Mujeeb-Kazi, 2008).

These innovations are revolutionizing wheat production, ensuring higher productivity while addressing global challenges such as climate change and food insecurity. An executive summary of the recent advances in wheat genome engineering technology was provided (Table 6).

3.2 Limitations of Wheat Genome Technology

Despite its potential, wheat genome research faces several limitations (Table 7) for executive summary):

3.2.1 Complex Genome Structure

Wheat has a large and highly repetitive genome (~17 billion base pairs), making genetic modification and sequencing more complex compared to other staple crops (Appels *et al.,* 2018). This complexity slows down progress in breeding programs.

3.2.2 High Costs and Resource Limitations

The implementation of genome editing and advanced breeding technologies requires substantial investment. Many developing countries lack the infrastructure and expertise to adopt these technologies, widening the agricultural productivity gap (Pingali, 2012).

3.2.3 Regulatory and Ethical Challenges

Strict regulations and public skepticism hinder the commercialization of genetically modified wheat. Concerns about GM crops' safety, environmental impact, and ethical considerations delay adoption in some regions (Lema, 2021).

3.2.4 Climate Change and Emerging Diseases

While wheat genome advancements have improved stress resistance, climate change continues to introduce new challenges, such as rising temperatures and emerging wheat diseases. The evolving nature of plant pathogens requires constant innovation in breeding strategies (Kumari and Sharma, 2022 and Sharma *et al.,* 2020).

Conclusions

Wheat remains one of the most economically important cereal crops globally, serving as a staple food for billions while contributing significantly to global trade, employment, and industrial applications. The economic importance of wheat extends beyond its role in food security, as it supports various industries, including milling, baking, livestock feed, and bioethanol production. However, the increasing global demand for wheat, coupled with environmental and biotic stress, necessitates continuous advancements in wheat breeding and biotechnology.Recent breakthroughs in wheat genome research, particularly in genome sequencing, CRISPR-Cas9 gene editing, and marker-assisted selection, have paved the way for the development of high-yielding, stress-resistant, and nutritionally improved wheat varieties. These innovations have the potential to enhance global wheat production efficiency, mitigate climate-related risks, and contribute to food sustainability. Nevertheless, challenges such as the complexity of the wheat genome, high costs associated with genetic research, regulatory restrictions, and public skepticism regarding genetically modified crops continue to hinder the full utilization of wheat genome technology.

To ensure long-term sustainability and maximize the benefits of wheat biotechnology, targeted investments in research, infrastructure, and policy reforms are necessary. Strengthening public-private partnerships, fostering international collaborations, and developing climate-resilient wheat varieties will be crucial in addressing emerging global food security challenges. Moreover, transparent communication and public awareness regarding the safety and benefits of genome-edited wheat can facilitate acceptance and adoption of these advanced technologies.While substantial progress has been made in wheat genome biotechnology, ongoing research, policy support, and strategic implementation are required to overcome existing limitations and unlock the full potential of these advancements. The future of wheat production lies in the integration of innovative genomic technologies with sustainable agricultural practices, ensuring global food security and economic stability in the years to come.

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