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# Triticum
## The Pillar of Global Food Security

*Edited by Vijay Singh Meena, Jai Prakash Jaiswal, Dinesh Jinger and Venkatesh Paramesh*

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*Edited by Vijay Singh Meena,*
*Jai Prakash Jaiswal, Dinesh Jinger*
*and Venkatesh Paramesh*

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## Aims and Scope of the Series

The importance of agriculture cannot be overstated. It helps sustain life, as it gives us the food we need to survive and provides opportunities for economic well-being. Agriculture helps people prosper around the world and combines the creativity, imagination, and skill involved in planting crops and raising animals with modern production methods and new technologies. This series includes two main topics: Agronomy and Horticulture, and Animal Farming. This series will help readers better understand the intricacies of production agriculture and provide the new knowledge that is required to be successful. The success of a farmer in modern agriculture requires knowledge of events happening locally as well as globally that impact input decisions and ultimately determine net profit.

# Meet the Series Editor

W. James Grichar has been employed with Texas A&M AgriLife Research for over 45 years with an emphasis on research in agronomy, plant pathology, and weed science. He obtained his BS from Texas A&M in 1972 and his Masters of Plant Protection in 1975. He has published 195 journal articles, over 330 research reports and briefs, 11 book chapters, and over 300 abstracts of profession meetings. He also directs research in many crops including corn, grain sorghum, peanuts, and sesame. He has held various positions in different professional societies including the American Peanut Research and Education Society, Southern Weed Science Society, and Texas Plant Protection Conference in addition to being Associate Editor for Peanut Science and Weed Technology. Significant accomplishments have included spearheading efforts to determine the optimum planting time for soybean production along the upper Texas Gulf Coast. These efforts have shown growers that soybean yields can be improved by 10 to 20% by following a late March to early April plant date. He also has been instrumental in developing a herbicide program for peanut production in the south Texas growing region. Through the development and use of herbicides that are effective against major weed problems in the south Texas region, peanut yields have increased by 25 to 30%.

# Meet the Volume Editors

Dr. Vijay Singh Meena is a Senior Scientist at ICAR-Indian Agricultural Research Institute, Regional Station, Samastipur. He specializes in climate-resilient agriculture, soil health, and sustainable farming practices. He has received several prestigious honors, including the INSA and NAAS Young Scientist Awards, as well as recognition as a Top Agri-Pioneer by the World Food Foundation. Dr. Meena has edited over a dozen books and contributes to major agricultural journals. His research at CIMMYT-BISA significantly advanced climate-smart farming. He actively engages in global forums, working to promote agri-food systems and nutritional security.

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Dr. Dinesh Jinger is a Scientist at ICAR-Indian Institute of Soil and Water Conservation, Research Centre, Chandigarh. His work focuses on agroforestry, natural farming, conservation agriculture, and land rehabilitation in semi-arid regions. He has developed innovative agri-horti and silvi-pasture systems for degraded ravine lands. An award-winning researcher, he has led nine research projects and authored over 50 scientific articles. Dr. Jinger's contributions toward ecosystem services, energy efficiency, and soil health are shaping sustainable land use strategies in tribal and marginal farming areas.

Dr. Venkatesh Paramesh is a Scientist (Agronomy) at ICAR-Central Coastal Agricultural Research Institute, Goa. He specializes in integrated farming systems, coastal agriculture, and ecosystem modeling. His work on nutrient cycling and energy efficiency in farming systems has directly benefited coastal farmers, including innovations that led to national recognition for associated farmers. Dr. Paramesh has led and collaborated on six research projects and published 45 research articles. His contributions to sustainable agriculture, especially during the COVID-19 pandemic, have earned him acclaim in both scientific and farming communities.

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# Preface

Wheat (*Triticum aestivum* L.) remains a cornerstone of global food systems, feeding billions and making a substantial contribution to human nutrition and economic development. As the global population rises and climate patterns shift unpredictably, ensuring the sustainable intensification and resilience of wheat production is a paramount challenge and opportunity for the scientific community, policymakers, and farming stakeholders alike.

This edited volume brings together multidisciplinary perspectives to explore key dimensions of wheat research and development. The contributions address integrated approaches to pest management that minimize ecological footprints while maintaining productivity. They emphasize the role of genetic improvement, innovative breeding strategies, and advanced genomic technologies in developing resilient and high-yielding wheat varieties that are adapted to diverse agro-climatic conditions.

A major focus of the volume is the growing threat of abiotic stresses, such as salinity, drought, and post-flowering heat, as well as the emerging tools available to combat them. Genome editing, stress physiology, and gene expression analyses are highlighted as frontiers for enhancing stress tolerance in wheat. Alongside abiotic challenges, the book examines biotic stresses, particularly those posed by pathogens and mycotoxin-producing fungi, offering insights into host immune responses, pathogen resistance, and safe grain management.

The volume also contextualizes wheat research within the broader goals of food and nutritional security. Discussions on sustainable agriculture, circular economy principles, and green capitalism provide a socio-economic lens through which wheat production and policy can be reimagined. Furthermore, the role of wheat in combating hidden hunger through biofortification strategies is underscored, presenting the crop as not only a staple for caloric intake but also a vehicle for improved human health.

Regional variability, especially under climate change, is another recurring theme. The changing phenology and yield stability of wheat in Mediterranean and tropical systems are examined, revealing the necessity for location-specific adaptation strategies and integrated management practices that link agronomic knowledge with climate-smart innovation.

Together, the chapters provide a comprehensive synthesis of current knowledge, technological advancements, and future directions in wheat science. The contributors, ranging from geneticists and agronomists to food safety experts and socio-economic analysts, demonstrate how wheat can remain a cornerstone of sustainable agriculture and food security in the decades ahead.

We would like to extend our sincere appreciation to all the contributing authors for their insightful work and to the peer reviewers whose feedback strengthened the

scholarly quality of this volume. We are also grateful to the editorial and production teams at IntechOpen for their invaluable assistance throughout the publication process. Special thanks are due to our research collaborators and institutional colleagues who supported this endeavor in many forms.

We hope that this volume serves as a valuable resource for researchers, educators, policy experts, and practitioners committed to building a sustainable and food-secure world, one that is anchored by the enduring legacy of wheat.

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Section 1

# Genetic and Genomic Innovations for Future Wheat Challenges

**Chapter 1**

# Challenges in Wheat Breeding in the Twenty-First Century

*Leon Muntean, Ioana Virginia Berindean, Ionut Racz and Andreea Ona*

## Abstract

The chapter "Challenges in Wheat Breeding in the 21st Century" explores the profound impact of climate change and population growth on wheat cultivation, emphasizing the urgent need to develop high-performing cultivars. The depletion of natural resources, such as water and soil, further complicates this process. The role of wheat in the circular economy is highlighted, providing insights into the efficient use of agricultural resources. New genomic techniques and next-generation sequencing are revolutionizing wheat breeding, accelerating the identification of favorable genes for adaptability and constant high yield, which are vital for future food security. To address current and future challenges, an integrated approach combining new breeding techniques, sustainable agricultural practices, and circular economy principles is essential. Wheat breeding programs should focus on developing varieties that are resilient to abiotic stresses, resource-efficient, and adapted to local conditions. International collaboration and interdisciplinary research are essential to supporting innovation and ensuring global food security. Furthermore, lobbying for the extensive adoption of improved, cost-effective cultivars will ensure accessibility for farmers. By aligning breeding goals with market demands and environmental sustainability, the foundation for a resilient and sustainable agricultural future can be established.

**Keywords:** climate changes, population growth, genetic resources, new genomic techniques, next-generation sequencing, circular economy

## 1. Introduction

Wheat, a staple crop for over 35% of the global population, plays a pivotal role in food security and economic stability [1]. However, the twenty-first century has ushered in a series of challenges threatening wheat production. Climate change intensifies abiotic stressors, such as heat and drought, while shifting population dynamics demand higher yields and better grain quality [2]. Simultaneously, finite natural resources, such as water and arable land, strain agricultural systems [3]. Furthermore, consumer preferences lean toward sustainably produced, nutrient-rich, and environmentally friendly products [2]. Modern wheat breeding programs must address these challenges by incorporating advanced genomic technologies, such as CRISPR-Cas9 and marker-assisted selection, alongside interdisciplinary approaches. These innovations aim to improve yield, resilience, and resource-use efficiency [4].

The advancement of wheat breeding aligns with technical evolution, resulting in the integration of modern techniques into the successful development of new wheat breeding cultivars. For example, thanks to doubled haploid technology, the Plant Breeding Institute at the University of Sydney has decreased the 10-to 12-year time it takes to generate new wheat varieties in half, down to 6 years. Producing homozygous lines at a rapid rate, this strategy speeds up breeding efforts [5]. A new approach to wheat breeding is being developed at the International Maize and Wheat Improvement Center (CIMMYT) by combining state-of-the-art AI with genetic variety. To combat issues of food insecurity on a worldwide scale, this strategy seeks to breed wheat types with increased yield and tolerance for difficult environments [6]. Significant progress has been made with the production of HB4 wheat, which has been genetically modified with sunflower genes to increase drought tolerance. Pending additional experiments, the United States Department of Agriculture has determined that this wheat is safe to cultivate [7].

Considering the above, the present paper provides a comprehensive analysis of the current barriers and opportunities in wheat breeding, emphasizing the importance of collaborative research and sustainable practices to meet future demands.

## 2. Impact of climate change

Climate change significantly impacts wheat productivity and adaptability. Rising temperatures have led to shifts in cultivable areas, with some regions experiencing increased potential for wheat growth due to warmer climates, while others face yield reductions due to heat stress. **Figure 1** illustrates the negative impact of heat and water stress on wheat plants. For instance, wheat yields are projected to decrease by up to 6% for every degree of temperature increase beyond optimal ranges (16–23°C during vegetative and generative stages). Conversely, new areas may become suitable for wheat cultivation, particularly at higher latitudes, improving global wheat distribution.

Over time, plants have demonstrated their ability to adapt to different environmental conditions, but the sharp increases in temperatures in recent decades are pushing wheat plants' ability to adapt to the limit. Temperature is one of the major concerns influencing wheat growth and development, limiting its genetic potential. The global temperature is predicted to increase by 2.5–5.8°C until the 2100s; therefore, the frequency of temperature shocks will be much higher for wheat plants, generating profound disturbances at the plant level. Depending on the biological material, the overoptimal temperature declines by 0.07% per °C grain yield. The percentage of yield reduction can reach up to 6%, depending on the wheat stage, for each degree increase in temperature [8]. Even if wheat is a C3 plant type, and the optimal temperature for plant development—depending on the phenophase, ranges between 16°C and 23°C during the main vegetative and generative stages [9], each degree increase in temperature has a crucial effect on plant developing traits. Heat stress, depending on its magnitude and duration, causes the slowing down of the growing process and morpho-physiological alterations, hindering the development processes and increasing yield loss. High temperature and thermal stress affect cell

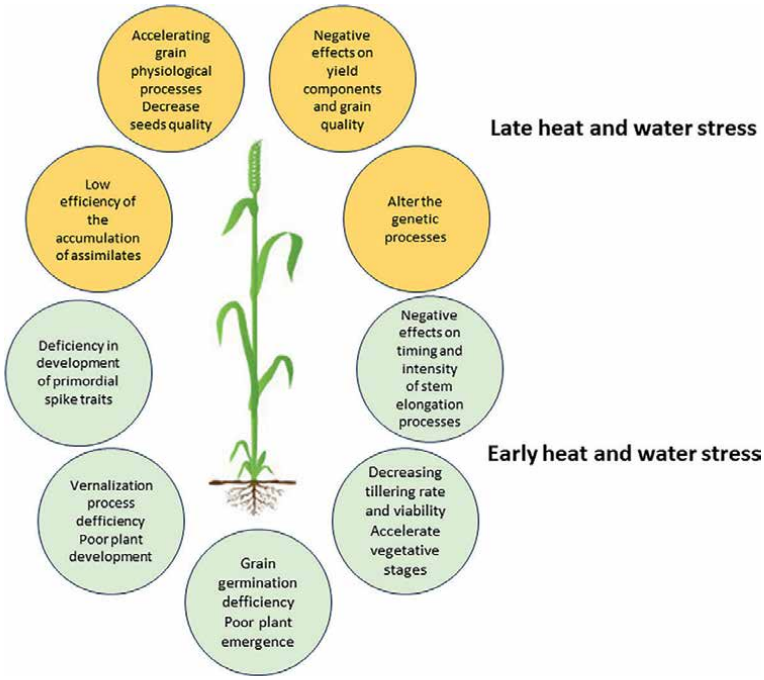


**Figure 1.**
*Climate change consequences on wheat plants. Original design by I. Racz.*

homeostasis [10], causing enzyme denaturalization and leaf dehydration, disrupting the osmotic regulation mechanisms of plants. Rising temperatures over optimal (>32°C), especially in the reproductive stage, disrupts the process of microgametogenesis and microsporogenesis, causing abnormal gamete development and spore abortion [11]. A high temperature of 42°C declines the main oxido-reducing enzyme synthesis and efficiency by reducing green leaf area due to the decrease in chlorophyll and carotenoids content, which causes leaf senescence [12].

Climate change and water are indissolubly linked the linkage between these being more intense due to global warming, which favors the increased intensity of extreme events—drought and precipitation. The water status is generally found to be disorderly under changing temperatures, the rainfall patterns being unpredictable, which promotes both water scarcity and water-related hazards. Pre-generative and generative stages are the most important phenophases of wheat, the plant's requirements for water are high in these periods, which can lead to decreased productivity. Vogel [13] observes that climate changes in Europe, especially rainfall anomalies, can determine a large variation of 28–63% in wheat grain yield. On the other hand, the influence of water availability on wheat grain yield is not generated by the rainfall level but rather by precipitation dispersion during the growth season, which is unevenly distributed throughout the development phases of winter wheat [14].

Extreme weather events are expected to create precarious situations in wheat crops, pushing their adaptability to marginal limits. Long periods without rainfall during the intensive plant growth or generative stages, accompanied by short or prolonged high temperatures, have been increasingly present in the last few years. In order to normal development and to reach its yield potential, wheat plants need a normal and equitable distribution of 350–550 mm of water during the growing season, especially in the pre- and post-anthesis stages. Unfortunately, in the last decade, even if the rainfall level is close to these requirements, the distribution of rainfall is quite chaotic, alternating periods of drought with periods of torrential rain, and the predictions for these events are predicted to be four times as frequent by 2080 [15]. Regarding the temperature, in previous years, new records were set for recorded temperatures. Unseasonal periods of extremely high temperatures occurred for short periods in winter, late spring, or summer and affected plant development due to the hazardous atmospheric circulation [16].

If a positive effect of global warming can be highlighted [17], it is because the increase in global temperatures has allowed wheat to be cultivated in areas where a few decades ago this was not favorable. This is because the increase in temperatures has caused certain land surfaces previously characterized as having a low degree of favorability to higher degrees of favorability, while certain favorable areas for wheat crops have been downgraded because of soil erosion.

Climate change has an important impact on wheat grain yield and quality indices. As one of the main food sources, high grain yield and superior quality must be the main attributes of each wheat harvest. Both are complex genetic traits that are influenced by genetic factors, environmental conditions (biotic and abiotic factors), and their interaction. Environmental conditions (abiotic factors) can limit the expression of the genetic potential of wheat genotypes. In the case of wheat productivity, both water availability and temperature can have a crucial effect depending on the level and timing, which can cause a global average reduction of over 50% [18]. For grain quality, high temperature can have an antagonistic effect on protein content, improving the total protein content but decreasing the end-use protein quality [19], as an effect of decreasing the albumin and globulin content [20]. The same effect was observed on starch content [21]; high temperature inhibits the starch accumulation in grains. A positive correlation was observed between gluten content and heat stress during the final plant stages [22], alongside post-anthesis high temperature, which decreases the starch granules due to the low amylopectin content [23].

Wheat plant adaptation to different stress factors can be achieved using two mechanisms: by avoiding the factors that cause that stress or by improving tolerance, respectively increasing resistance, to the respective factors. In the case of avoiding the mechanism of stress factors, there are several opportunities to achieve this goal through crop management: different sowing times, tillage or crop systems, chemical treatments—osmoprotectants, phytohormones, signaling molecules, trace elements, etc. The second mechanism for improving wheat plants involves strategies for genetic modification against stress factors. The improvement of various physiological traits and biochemical compounds/parameters has been found to contribute to heat stress and drought tolerance through higher photosynthetic rates, staying green, and chlorophyll content [24]; antioxidant enzymatic activity and malondialdehyde content, proline content, canopy temperature depression, cell membrane injury, and transpiration rate [9, 25]. Salt stress is one of the abiotic stress factors that limits wheat productivity due to the limiting morpho-productive expression traits and poor tolerance to this element, which can influence seed properties and plant growth by inhibiting the physiological attributes [26]. The improvement of wheat tolerance to salt stress involves crossbreeding this species with its wild relatives, which exhibit salt tolerance (*Elytrigia* sp., *Thinopyrum* sp., *Leymus* sp., etc.).

## 3. Population growth and food demand

The global population growth predicted to exceed 10 billion by the 2080s, will significantly increase demand for wheat, with estimates indicating a 60% rise in consumption by 2050. This trend highlights the urgent need for breeding programs to enhance yield and quality. Climate change poses additional challenges in meeting this demand, particularly in South Asia and Africa, where wheat yields are expected to decline by 15–16% by mid-century due to heat and drought stress.

In addition to an increasingly large population globally, a variety of other factors are continuously influencing the evolution of consumer preferences. Climate change, better health, increased awareness of food waste, urbanization, worries about animal welfare, and a desire to reduce the environmental implications of food production [2] directly affect global wheat demand. Countries in South Asia and Africa are expected to see the most severe effects of climate change, with average yield losses of 15% and 16% by 2050, respectively, leading to a 1.9% fall in world wheat production by mid-century. Though wheat breeding for new traits offers hope for adapting to climate change, the impact of these efforts will differ by region and may be minimal in rainfed areas due to water and nitrogen stress. Adaptations to new growing regions may be necessary in response to rising temperatures and drought [27]. Wheat consumption habits might change in response to these developments since they will all have an effect on the global price of wheat. The increasing demand for healthier products among customers is also driving a change in the food and beverage business worldwide. The industry needs to adapt in order to meet the growing purchasing power of younger generations who are more concerned about the effects of their decisions on their health and the environment [28]. A trend toward organic, gluten-free, genetically modified organism (GMO)-free, and organic grains has emerged in recent years [29]. Forecasts indicate that the worldwide organic grain farming industry will grow from its 2023 valuation of $40.34B to a whopping $131.18B by 2032 [30]. Labels that indicate farms have a low environmental impact, such as organic, non-GMO, cage-free, grass-fed, and solar/wind-powered, will become increasingly significant since younger generations have become wiser and are willing to pay a premium for products that meet the most stringent certification standards [31].

Wheat is a primary cereal for food processing because of its unique chemical composition and remarkable technological qualities; in many countries, it is known as a "bread cereal" [32]. Agricultural practices, genotype, and habitat conditions are among the numerous factors that determine the quality and yield of wheat cereal [32]. Improving agronomic performance while simultaneously improving qualitative traits to suit the needs of various international markets and end-users, including producers, millers, bakers, and consumers, is a frequent problem for wheat breeding programs worldwide [33]. It is challenging to produce wheat with superior bread-making quality, especially in organic agriculture, due to reduced nitrogen availability, which results in lower grain protein concentrations [34]. Worldwide wheat output could be endangered by both biotic and abiotic factors. Global warming and other forms of climate change are expected to reduce wheat productivity and nutritional value, posing a threat to food security. Breeding research and technology have come a long way, but there are still opportunities to create high-yielding, high-quality cultivars. Modern plant breeding and advancements in management practices have significantly contributed to the annual increase in crop productivity, which is approximately 0.8–1.2%. However, this rate of progress is insufficient to meet the dietary and nutritional requirements of the projected global population [30]. An annual increase of 1.4–1.7% in world wheat output is required to meet the anticipated rise in global demand, as well as the abiotic and biotic threats to food security [35].

## 4. Depletion of natural resources

Water and soil resources are critical for sustaining wheat production. Agriculture accounts for 71% of global freshwater use, making water efficiency vital. Strategies such as precision irrigation, drought-tolerant varieties, and conservation tillage can mitigate resource depletion. Advances in soil health through crop rotation and organic amendments also help preserve productivity.

Strategies must be adapted to the water regime of each area to effectively manage water resources. Better water retention in soil is required in rainfed agriculture, by encouraging minimum soil disturbance, maintaining permanent soil cover with crop residue and live mulches, and diversifying plant species [3], as well as by using rainwater collecting techniques [36]. In contrast, for drought-prone areas, strategies such as drip irrigation, which minimizes water loss through evaporation [37], the reuse of treated wastewater for irrigation [38], and the cultivation of drought- or heat-tolerant varieties [39] can be implemented.

Investing in new irrigation systems or the rehabilitation and modernization of current ones will greatly increase the output of irrigated systems [40]. The most profitable alternative and thus the most adopted in irrigated systems with good control over water is precision agriculture [41]. Solar-powered irrigation pumps that improve water efficiency, lower groundwater usage, reduce dependence on fossil fuels, diminish greenhouse gas emissions, and give farmers consistent income would be another alternative [42].

Wheat, a crop with high water consumption and low water use efficiency, is one of the main cultivated plants in arid and semiarid regions [43]. In water-deficient areas, better water management could close production gaps and improve food security and nutrition. Irrigation methods significantly influence the growth and development of wheat plants, resulting in better control over productivity and quality [44]. Still, the lack of rainfall can drastically reduce cereal production even in irrigated areas [45]. In countries aiming at wheat self-sufficiency, the water resources utilized for irrigation must be handled carefully since they have been vital in declining groundwater levels [46].

Wheat's irrigation techniques offer a set of benefits and limitations as well: surface irrigation is low-cost but labor-intensive and prone to water loss and soil erosion [47]; sprinkler systems offer good control of the water microclimate, evapotranspiration, and fertigation, and reduce ambient crop temperature but come with high capital costs and potential wind loss [48]; and micro-irrigation provides excellent water and fertilizer efficiency and controls soil salinity but requires high initial investment and maintenance [49].

The expansion and intensification of agriculture have caused considerable pressure on global resources, leading to the extreme deterioration of 25% of the agricultural land on Earth [50]. The main factor of soil deterioration, erosion has had a significant impact on agricultural output, particularly in nations including India, China, Iran, Israel, Jordan, and Pakistan, where yields have dropped by as much as 20%. According to Pimentel [51], annual production losses from worldwide soil erosion come to $400 billion.

By regular tillage, which damages soil structure and causes compaction, intensive farming techniques can negatively affect wheat harvests, thus reducing water and air penetration and so restricting root development [52]. Monocropping exhausts minerals and nutrients, thereby increasing the need for synthetic fertilizers [53]. Synthetic fertilizers used excessively reduce organic matter and humus levels, acidify the soil, and lower microbial biodiversity [54]. The absence of plant waste amplifies wind- and water-related soil erosion, thereby depleting the layer of rich soil and lowering the water retention capacity [55].

To prevent soil degradation, a combination of sustainable practices and advanced technologies is essential for wheat crops. Conservation tillage systems (no-till, ridge-till, and mulch-till) [56], strip cropping [57], cover cropping [58], crop residue retention [59], crop rotation [60], and organic fertilization [61] have demonstrated their ability to rebuild soil structure, increase water infiltration, reduce erosion, and enhance soil organic matter content. Precision agriculture technologies, such as variable-rate fertilization [62], drip irrigation [63], and soil moisture sensing [64], facilitated by drones and satellite imagery [65], offer the potential to optimize resource use and minimize environmental impacts. Nevertheless, challenges such as the high initial costs of precision agriculture technologies and the longer-term nature of improvements associated with practices like crop rotation and organic fertilization must be considered.

In the context of the depletion of natural resources, plant breeding can be a viable alternative to many of the challenges mentioned. The introduction of wheat cultivars that can tolerate drought and heat, which are able to perform well in water-limited situations, has the potential to reduce the dependency on too much irrigation and lower water stress on soils [66]. In a similar line, wheat cultivars showing effective nutrient absorption can reduce the reliance on chemical fertilizers, hence reducing soil pollution and degradation [67]. By reducing pesticide use, creating wheat genotypes resistant to pests and pathogens could help to improve soil biodiversity [68, 69].

## 5. Circular economy

From a wider point of view, the importance of a circular economy in agriculture resides in the fact that it supports sustainable resource management, reduces waste, and increases system resilience [70]. As far as wheat is concerned, it enables the development of high-yielding and resource-efficient varieties that contribute to food security and environmental conservation [71]. The circular economy principles can help wheat cultivation change from an input-intensive linear model to a closed-loop system that is much more resource-efficient and has less environmental impact [72].

The main goals of wheat breeding in a circular economy are to reduce waste, recycle, or give new purpose to by-products, and to maintain resource efficiency within the system [73]. In **Figure 2** we can see the wheat production process in a circular economy. The key elements of this approach include increasing nutrient use efficiency by breeding wheat varieties that uptake and utilize nutrients efficiently, thereby reducing dependence on synthetic fertilizers and minimizing nutrient runoff. Similarly, breeding drought-tolerant wheat varieties to increase water use efficiency helps conserve valuable water resources, especially in drought-prone regions [74].

The other main emphasis is on root system architecture, in which breeding aims to improve root systems to increase soil structure, reduce erosion, and promote soil health [73]. In addition, developing wheat varieties that contribute to soil organic


**Figure 2.**
*Key pillars of wheat production in a circular economy. Original design by L. Muntean.*

matter *via* root exudates [75] and crop residues [59] will further improve long-term soil fertility. Another important area is straw utilization, where breeding programs aim to develop wheat varieties whose straw can be transformed into bioenergy [76], animal feed [77], or biodegradable materials [78] to reduce agricultural waste.

Improvement of grain quality is equally important to reduce postharvest losses and to have higher benefits in terms of nutrition [79]. Moreover, breeding for wheat varieties possessing bran and germ, usable in food, nutraceuticals, or animal feed, will increase the value of the by-products while reducing waste [80, 81].

Participatory breeding is the way that farmers and other stakeholders can be involved in the breeding process to ensure new varieties are suited to local needs and conditions, which enhances adoption and sustainability. Another important focus is low-input wheat varieties that can grow well with minimal resources, thus reducing the ecological impact of cultivation. It is equally important that the new wheat varieties should be economically feasible for farmers to encourage wide-scale adoption and long-term sustainability. Aligning breeding goals with market requirements for sustainable and high-caliber wheat products enhances both economic stability and environmental sustainability [82, 83].

## 6. Advances in genomic techniques and next-generation sequencing

Genome-wide association studies (GWAS) are techniques frequently used to explore genotype-phenotype connections, aided by developments in next-generation sequencing (NGS) technologies [84–86]. Recent progress in NGS has enabled the identification of high-density SNPs, significantly enhancing marker resolution [87, 88].

GWAS methods analyze the connection between markers, like single nucleotide polymorphisms (SNPs), and the phenotype of a target trait noted in large material collections [89]. Key factors, like population structure, phenotypic variability, linkage disequilibrium (LD), and allele frequency influence the statistical power of GWAS [89]. GWAS data analysis relies on linkage disequilibrium (LD) and offers significantly higher resolution for understanding the genetic architecture of complex traits compared to traditional QTL mapping [90, 91]. GWAS has become a robust method for unraveling the genetic core of complex traits by pinpointing specific genomic regions, referred to as quantitative trait loci (QTLs), that influence phenotypic variation [85]. This is accomplished by utilizing a sufficient number of genetic markers and leveraging linkage disequilibrium (LD) between alleles [92, 93].

GWAS has limitations, including its inability to identify rare alleles and the impact of unaccounted or overcorrected population structure [94, 95].

Even though GWAS is used in wheat, it is challenging due to its polyploidy, large genome, and incomplete genome sequence, which complicate the assignment of markers to highly similar homologous chromosomes [96]. Still, it has been effectively applied to map QTL for traits like grain yield, disease, and quality in wheat [97] and for the identification of genomic regions related to grain morphology and stripe rust resistance in synthetic hexaploid wheat [98, 99]. **Figure 3** illustrates the genomic approaches employed in wheat breeding.

Clustered Regularly Interspaced Short Palindromic Repeats (CRISPR-Cas9) is a revolutionary gene-editing technique that allows for precise modifications to DNA within organisms. It has quickly become one of the most influential tools in molecular biology and genetic engineering [23, 85]. The CRISPR/Cas9 system has particularly transformed plant biology and agriculture, offering unique opportunities for accurate genetic alterations and the creation of enhanced crop varieties [85].

CRISPR/Cas9 expression cassettes, along with selectable marker genes, are typically delivered to plant cells using *Agrobacterium tumefaciens* or biolistic transformation methods [23]. However, these approaches require time-consuming, labor-intensive callus culture and regeneration processes, making them only suitable for genotypes that can undergo cell culture and regeneration, limiting their use in major crops like wheat, maize, and soybean [23]. To address these limitations, the in-planta particle bombardment (iPB) method was developed, which targets the shoot apical meristem (SAM) for transformation in wheat, offering a more efficient alternative.

Thanks to its remarkable simplicity and efficiency, CRISPR/Cas9 has rapidly been applied across a wide range of organisms. The technology's first use in bread wheat involved introducing targeted mutations in the A genome homoeoallele of TaMLO [100–102]. In addition, high-amylose wheat was produced through targeted mutagenesis of TaSBEIIa in the modern winter wheat cultivar Zhengmai 7698 (ZM) and the spring wheat cultivar Bobwhite using CRISPR/Cas9. This approach offers a new pathway for breeding wheat varieties with enhanced nutritional value [103].

Gene silencing is a process through which cells deactivate large regions of chromosomal DNA without altering the genetic code. It refers to the "turning off" of a gene by cellular mechanisms that do not involve genetic modification. In this process, a gene that would normally be expressed is silenced by cellular machinery. The silencing occurs when the target DNA is incorporated into heterochromatin, a form of DNA that is naturally inactive [104]. Gene silencing is a broad term encompassing

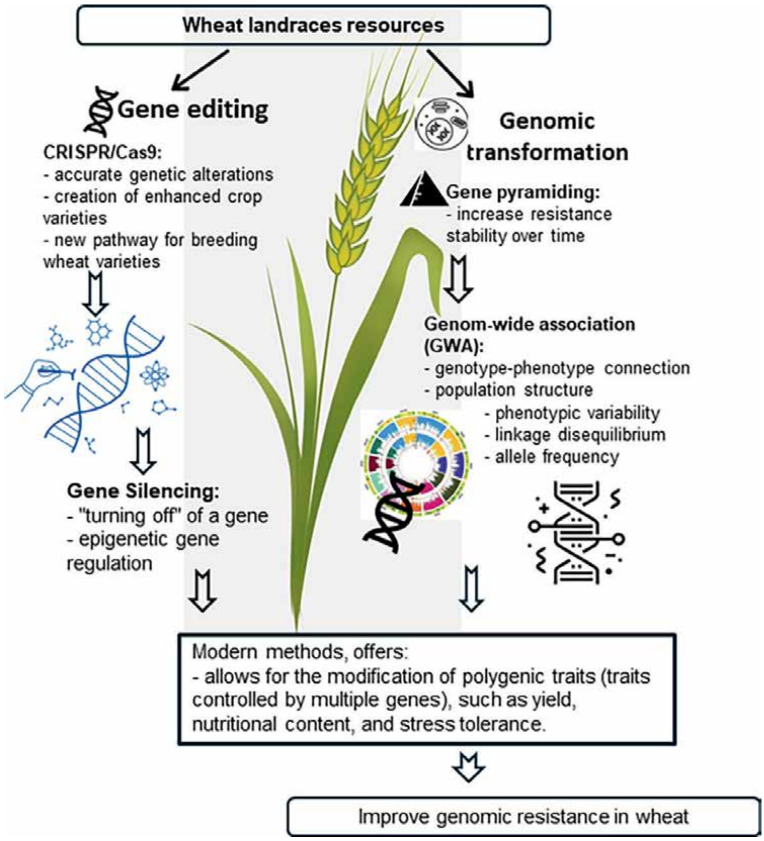


**Figure 3.**
*Genomic techniques in wheat breeding. Original design by I. Berindean.*

epigenetic gene regulation mechanisms and plays a key role in the differentiation of various cell types [104]. Genes can be regulated at both the transcriptional and posttranscriptional levels. Transcriptional gene silencing occurs when histone modifications create a heterochromatin environment around a gene, preventing access by transcriptional machinery such as RNA polymerase and transcription factors [104]. "Silencing" refers to the temporary inhibition of a specific gene's expression, preventing it from producing a message that could otherwise lead to an undesired effect. It is used in several categories of plants, including wheat.

In wheat, gene silencing is used in the case of insects, nematodes, viruses, and fungi [105].

Gene pyramiding (GP), or gene stacking, involves incorporating multiple resistance (R) genes into a single plant to enhance its disease resistance, resulting in a genotype that carries all the targeted genes, thereby improving resistance durability [85, 106]. In addition to providing stronger protection against pests and pathogens, gene pyramids increase resistance stability over time, lowering the likelihood that all genes will be overcome at once, particularly when broad-spectrum R genes are used [107].

Stripe rust, caused by *Puccinia striiformis* f. sp. *tritici* (Pst), is a major disease of wheat, and developing resistant cultivars is the most effective control method [108]. While many Yr resistance genes have been identified, only a few are effective against the current epidemic Pst races [108]. Research shows that the number of pyramided Yr genes is strongly correlated with increased resistance to stripe rust, so genes like Yr15, Yr62, and Yr65 are effective against current Pst races, and pyramiding more than four effective or partially effective Yr genes provide sufficient resistance [108]. Additive and epistatic effects were also observed in certain gene combinations, such as Yr26 + Yr48, Yr30 + Yr64, and Yr30 + Yr48, and additionally, Yr-gene pyramiding lines with favorable agronomic traits were developed, offering a durable solution for controlling stripe rust in wheat breeding [109].

Marker-assisted selection (MAS) is an innovative technique that uses molecular markers linked to resistance genes and enables rapid and precise selection of desirable traits in crops [85]. Recently, molecular markers have become valuable tools in agronomic sciences for analyzing genetic variation, effectively linking phenotypic and genotypic differences [109].

MAS improves crop breeding by overcoming the limitations of traditional phenotype-based methods, enhancing efficiency in pyramiding multi-allelic traits for high-yielding cultivars [110]. Also, MAS allows selection based on individual plants, efficient identification of recessive genes, and trait evaluation under limited field conditions, such as root traits or disease resistance, reducing replication needs and increasing selection intensity [110].

## 7. Importance of interdisciplinary research

Innovative strategies are needed in the agricultural sector, particularly in crop breeding, to deal with the pressing concerns of climate change and food security on a worldwide scale [111]. The complex process of plant breeding involves numerous different fields of study and activities [112]. For wheat breeding programs to be successful, it is vital to bring together professionals focused on adaptation to abiotic stress, control of wheat pathogens and pests, wheat breeding and genomics, nutritional quality, resource conservation, efficiency of nutrient use, and wheat agronomy [113]. In order to preserve or improve crops for human use, wheat breeders must also have a broad understanding of environmental, social, and economic factors in addition to genetics [112]. Complex traits may be analyzed successfully nowadays through genetics thanks to genomic advancements [114]. Experts in computer science, bioinformatics, computer simulation, artificial intelligence, machine learning, and statistical data processing are essential for collaborating on the massive amounts of data used in wheat improvement to increase the success of breeding programs. The use of artificial intelligence has been a game-changer in wheat breeding, opening-up new possibilities for making crops more resilient to and productive in the face of climate change challenges, making it easier to identify genotypes that work well in different environments through AI-driven phenotyping tools [111].

In order to encourage wheat breeding through cooperation, innovation, and the exchange of resources, public-private partnerships and international organizations have become indispensable [115]. Therefore, to solve the difficulties of wheat breeding, international organizations conduct research and development worldwide, genetic resource conservation, dissemination of knowledge, and international coordination of breeding plans to guarantee food security. Wheat breeding is revolutionized by multinational organizations and public-private partnerships, which use creativity and cooperation to address regional and global issues. Their work is essential to supply the rising demand for wheat while maintaining sustainability and adaptability to coming challenges [116]. Some of the most noteworthy organizations working to enhance wheat are:

International Maize and Wheat Improvement Center (CIMMYT) is leading in researching areas for some of the basic cereal crops like maize, wheat, triticale, sorghum, and millets. Wheat research at CIMMYT seeks to create disease- and pest-tolerant wheat lines that are rich in nutrients and high-yielding; develop genetically varied wheat varieties using more accurate phenotyping techniques such as remote sensing to achieve yearly genetic yield gains of at least 0.7% worldwide; offer possibilities for training in crop management research and wheat breeding; examine potential new markets for small-scale farmers [117]. The wheat collection stored at CIMMYT Genebank comprises around 150,000 accessions from over 100 countries, including bread wheat, durum wheat, and triticale landraces, cultivars, genetic stocks, breeding materials, and wild relatives [118].

The Food and Agriculture Organization (FAO) facilitates worldwide initiatives to improve wheat breeding, especially in developing nations, through technical help, financial resources, and policy promotion. Improving institutional capacity for effective crop variety creation and their dissemination through seed systems is FAO's goal through the multi-partner platform known as The Global Partnership Initiative for Plant Breeding Capacity Building (GIPB) [119].

The Wheat Initiative, formerly known as the International Research Initiative for Wheat Improvement (IRRIWI), is a rebranding effort that aims to strengthen partnerships among wheat researchers and national and international research programs that aim to improve food safety, nutritional value, and security in response to societal demands for more resilient and environmentally friendly agricultural production systems [113].

Together with plant scientists, wheat farmers, and public and private breeders, the International Wheat Genome Sequencing Consortium (IWGSC) set out in 2005 to collaborate on wheat genome sequencing. The goal of the IWGSC is to provide a high-quality bread wheat genome sequence that will enable both basic and applied wheat research, speed up the process of developing superior varieties, and enhance profitability across the sector.

Heat and Drought The Wheat Improvement Consortium (HeDWIC), a collaboration involving Consultative Group on International Agricultural Research (CGIAR), governments, and private partners to enhance climate-resilient wheat breeding, includes more than 90 countries. In order to better prepare wheat for a world where heat and drought are more common, researchers from around the world have come together to form this consortium. Specifically, it disseminates new technologies to wheat breeders all over the globe and helps the wheat growers and consumers to have more stable food supplies. Additionally, farmers will have the necessary skills to adapt to a changing climate, which will reduce the risk of devastating wheat crop losses [120].

The Durum Wheat Breeding Program, supported by collaborations between CIMMYT and private seed companies, enhances yield and quality. The primary objective of the CIMMYT Durum Program is to help developing countries increase the productivity of durum by providing germplasm that is disease-resistant, widely adapted, and high-yielding, with desirable end-use qualities. Also, acceptable levels of gluten strength are presently seen in CIMMYT germplasm [121].

International Wheat Yield Partnership (IWYP), whose objective is to enhance the genetic yield potential of wheat by 50% within a 20-year timeframe. IWYP is a worldwide, multi-year research project that combines resources from a wide variety of public and private organizations across several nations in order to provide wheat breeders with new elite genotypes. Through the creation of novel models, ideotypes of wheat in relevant breeding material, and related genetic tools for breeding, research is carried out to comprehend the physiological and genetic basis of increasing yield potential [122].

A multidisciplinary approach must be employed to both understand the fundamental processes of wheat breeding and find potential genes, QTLs, and traits that can be used to generate superior crops [123]. By combining the best features of public-private partnerships, this type of collaboration becomes an important force in contemporary wheat breeding. The knowledge and experience of public research institutions in basic science complement the cutting-edge technologies of private companies: molecular markers, genome editing tools (e.g., CRISPR), and high-throughput phenotyping [4]. To overcome the challenges posed by wheat breeding, a coordinated effort including a wide range of experts, technologies, and stakeholders is required. To guarantee global food security in the face of climate change and population expansion, an integrated strategy for wheat breeding is necessary in light of the current global concerns.

## 8. The role of international collaboration

To overcome and reduce the negative effects of climatic changes on wheat performance, the integration of various research entities into an international program is a primary goal. After all, the foundations of these collaborations were laid a long time ago, more than 80 years ago, along with the creation of International Agricultural Research Centers (IARCs), which included the International Maize and Wheat Improvement Center (CIMMYT), established in 1965 [124]. The International Center for Agricultural Research in the Dry Areas (ICARDA) represents an international organization that conducts agricultural research in nontropical drylands to provide the development of innovative, science-based solutions for communities across Central and West Asia, North Africa (CWANA), and the Middle East. Another international collaborative consortium (IWGSC) was founded in the early 2000s to enhance wheat breeding through an increased understanding of the molecular basis of wheat. Around the same time, the Borlaug Global Rust Initiative (BGRI) was founded as a global collaboration of scientists, farmers, and agricultural research institutions to improve genetic gain and increase disease resistance and climate resilience in wheat [125]. The Wheat Initiative (WI) was born in 2011 as a ministerial agreement of the G20 countries aimed at reinforcing synergies between members of the wheat research community and national and international research programs targeted to increase food security, nutritional value, and safety for sustainable and resilient agricultural production systems [113].

Common approaches have proven to play a crucial role in world food security through the so-called "Green Revolution" [124]. The success of international programs and initiatives supporting wheat breeding is difficult to estimate, but the role that these collaborations have in supporting food security can be appreciated based on the multitude of genotypes created. International programs and cooperation achieved through various entities have made it possible to maintain a high degree of improvement in wheat performance in different regions of the globe through the exchange of genetic materials [126] through the development and distribution of germplasm. Another successful international collaboration was the complete genome sequencing of wheat, which must help to understand traits inheritance and accelerate improvements in wheat breeding.

The impact of agricultural policies on wheat cultivation can have a significant role by adopting measures that can limit or expand both the areas occupied by this crop and the level of performance that this plant can achieve. The different views of independent states or groups of states on the use of unconventional plant breeding techniques, including wheat, can have a negative effect on both the effectiveness of this crop and its competitiveness. Also, the engagement of these entities in various global agreements to reduce negative anthropogenic effects on the environment can have a significant impact on how this plant will be continuously improved.

The genetic potential of wheat has reached a plateau in terms of improving performance, so international collaborations aimed at identifying old genotypes, local populations, or wild relatives to them will be key to continuing progress that will support demographic growth. Also, interdisciplinary approaches targeting plant physiology, phytopathology, agrochemistry, pyrotechnics, pedology, and other related disciplines will require the formation of working groups to create those ideotypes in which the specific characteristics for specific areas can be found.

## 9. Conclusions

The advancement of wheat breeding relies on the successful incorporation of innovative technologies, collaborative research efforts, and eco-friendly farming methods. The pressing challenges of climate change, population growth, and the depletion of natural resources demand immediate efforts to create resilient wheat varieties that achieve a balance between high yields and environmental sustainability. Essential strategies involve utilizing genomic tools, enhancing resource efficiency *via* precision agriculture, and embracing participatory breeding methods to guarantee solutions that are adapted to local conditions. Global cooperation will be essential in reaching these objectives, promoting innovation and fair access to enhanced wheat germplasm across the globe.

To ensure food supplies for future generations, the global wheat research community must focus on adaptability and sustainability. Integrating traditional knowledge with contemporary advancements allows wheat breeding to address existing challenges and create a sustainable agricultural future.

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Chapter 2

# Enhancing Wheat Resilience to Abiotic Stress: Genetic Mechanisms and Genome Editing Approaches

*Omnia Osama*


## Abstract

Abiotic stress, including drought, heat, and salinity, is a major yield-limiting factor for wheat production, which is crucial for facing food scarcity. With the growing challenges posed by climate change, improving wheat's resilience to abiotic stresses is essential for ensuring food security. This chapter explores the damaging effects of these stresses on wheat and examines the genes, pathways, and mechanisms involved in tolerance, focusing on key stress-related genes and their regulatory networks, such as the *TaDREB1* gene, which enhances drought tolerance by regulating water-use efficiency; *TaHKT1;5*, which plays a pivotal role in salinity tolerance by maintaining ionic balance; and *TaHSP17.4*, which improves heat tolerance by reducing oxidative damage and stabilizing cellular functions. It also discusses the potential of genome editing, like CRISPR-Cas9 and TALENs, to improve wheat tolerance to these abiotic stresses, offering a sustainable approach to enhancing crop performance to meet future food demands.


**Keywords:** abiotic stress, drought, salinity, heat stress, transcription factors, genome editing, CRISPR Cas9

## 1. Introduction

Wheat is one of the most important staple crops worldwide, with approximately 35% of the global population depending on it for feeding. Its cultivated area globally is over 220 million hectares, making it one of the most widely grown crops in the world. In 2023/2024, global wheat production reached approximately 785 million metric tons, which is considered a decrease compared to the previous marketing year 789 million metric tons [1]. This decline shows the vulnerability of wheat production to various environmental factors, such as climate change and abiotic stresses, including drought, heat, and salinity. Abiotic stresses such as drought, heat, and salinity significantly reduce wheat yields and are considered among the primary limiting factors for production. Drought alone can lead to yield losses of up to 50–60%, particularly during the flowering and grain-filling stages. Heat stress, which affects wheat during critical growth periods, has been shown to reduce yields by 20–40%, with higher temperatures disrupting reproductive processes. Salinity, which impacts more than 20% of irrigated agricultural lands globally, can reduce wheat yields by 30–50%, depending on the severity of the stress and the wheat variety's tolerance [2]. The severity of these stresses is maximized by present climate change. Climate change is expected to increase variations in both abiotic and biotic stresses over time, which could lead to substantial shifts in wheat yields and grain quality. Predictions of a 2°C rise in global mean temperatures suggest that these stresses will change in both timing and intensity, with their geographic distribution expanding [3], making it crucial to explore effective strategies for enhancing wheat's resilience to these abiotic stresses. Genome-editing technologies, such as CRISPR-Cas9, have emerged as powerful tools for developing wheat varieties with improved tolerance to abiotic stresses. Recent advancements, such as editing stress-related genes like *TaHKT1;5-D* for salinity tolerance and *TaDREB2* for drought resilience, offer promising results in mitigating the damaging effects of these stresses. These innovations align with global efforts to secure food production and strengthen climate resilience [4, 5]. This chapter explores the genetic mechanisms underlying wheat's resilience to abiotic stresses and discusses how genome-editing technologies can be leveraged to improve wheat productivity, contributing to the achievement of SDG 2: Zero Hunger and SDG 13: Climate Action.

## 2. Drought

### 2.1 Drought damaging effect on wheat

Water scarcity is a major global threat to agricultural sustainability worldwide, raising serious concerns about food insecurity. In wheat, drought stress has been reported to drought stress significantly reduce wheat yield, with reported reductions ranging from 25 to 62.75%, depending on severity. This impact extends to yield components, including grain numbers per spike (38–50%), 1000-kernel weight (16.4–19.42%), and plant height (14.7–34.45%). These figures underscore the urgent need for developing drought-tolerant wheat varieties to sustain productivity under water-limited conditions. Drought is an adverse abiotic stress factor that significantly reduces crop yields, inhibits root development and limits water uptake, disrupts photosynthetic activity by inhibiting leaf growth and increasing photorespiration. These effects collectively hinder plant growth and development [6, 7].

Drought stress increases the production of reactive oxygen species (ROS) leading to oxidative stress. In response, antioxidant enzymes such as superoxide dismutase (SOD), peroxidase (POD), catalase (CAT), and glutathione reductase (GR) are activated to mitigate cellular damage. The concentration of malondialdehyde (MDA) as drought intensifies can indicate the degree of oxidative stress to which the crop is experiencing, the rapid rise level of malondialdehyde causes cellular damage. Plants improve membrane stability by the synthesis of soluble protein, soluble sugar (SS), and proline (Pro). Therefore, photosynthesis, plant morphology, antioxidant properties, and osmoregulation are essential indicators for studying the effects of drought stress [8].

### 2.2 Drought coping mechanisms

Plants have evolved various mechanisms to mitigate the adverse impacts of drought across morphological, physiological, biochemical, and molecular levels. These mechanisms include: (1) Drought avoidance includes morphological adjustments to enhance water usage under mild or moderate drought stress conditions by reducing water loss *via* leaf rolling, increasing epidermal waxes accumulation, maintaining cell membrane stability and cell wall elasticity maintain normal cellular water potential and osmotic pressure, reduce oxidative damage and improve cell antioxidant capacity enhancing the water uptake ability through adjustments of architecture of root system either by deep root system to access groundwater or lateral roots for surface moisture, enhancing the water storage abilities in specific organs. (2) Drought escape where plants adjust their life cycle by accelerating developmental stages in response to moisture availability with early flowering and shorter life cycles. (3) Drought tolerance is the plant ability to maintain physiological activities at the molecular level under severe drought stress conditions through the regulation of drought-responsive genes involved in ABA signaling and antioxidant defenses. Under drought stress conditions; sensitive wheat plants accumulate $H_2O_2$ resulting in the downregulation of antioxidant enzyme activities. Tolerant plants respond by overexpression of genes that are related to signal transduction factors, protein kinases, transcription factors, and ABA receptors or proteins involved in metabolisms, osmotic regulation, and ROS transportation, other stress-responsive genes such as transcription factors, WAX INDUCER/SHINE1 (WIN/SHN), Drought Response Element Binding Factor (DREB), WRKY, Nuclear Factor (NF-Y), MYB, NAC) (4) Drought recovery refers to the plant capability to resume growth post-drought through rehydration capacity, osmotic adjustments, photosynthetic recovery, and root regrowth (**Figure 1**) [7, 9–12].

### 2.3 Drought stress responsive genes

Wheat is known to have a complex genome. Drought stress triggers a series of molecular processes involving crosstalk between different genetic networks and endogenous factors such as plant hormones, reactive oxygen species (ROS) Scavenging genes, transcription factors, and others all of which play a role in drought stress tolerance.

ABA is a primary stress hormone that regulates plant response to drought. ABA signaling mediates the expression of various drought-responsive genes such as stomatal movement, the modulation of the root system, and the expression of various stress-related genes. The overexpression of the *TaHsfC3-4* gene, which is a member of the heat shock transcription factor C (HsfC) subclass enhanced tolerance to drought, shows that *TaHsfC3-4* has a positive role in the ABA signaling pathway and drought tolerance [13]. Overexpression of *TaABFs* (ABA-Binding Factor)-enhanced *TaPYL1-1B* (acid ABA receptor) ABA sensitivity leading to improved drought tolerance [14]. Calcium-dependent protein kinases *TaCPK34* protein upregulation in wheat under drought stress indicates that the *TaCPK34* gene plays positive roles in wheat response to drought stress through regulating ABA-dependent

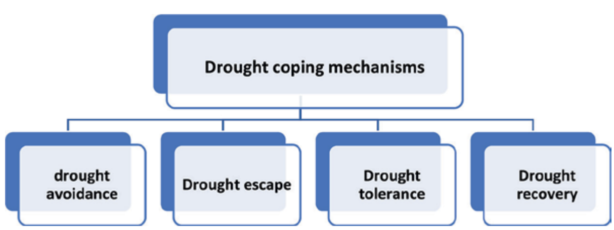


**Figure 1.**
*Drought coping mechanisms.*

genes [15]. Overexpression of wheat bZIP transcription factor gene *TaFD-Like2-1A* (*TaFDL2-1A*) improved wheat drought stress tolerance by enhancing ABA biosynthesis, ABA responses, and ROS scavenging. *TaFDL2-1A* binds directly to the promoter of both *TaRAB21s* and *TaNCED2s* activates their expression, resulting in enhanced ABA responses and endogenous ABA accumulation. Moreover, overexpression of *TaFDL2-1A* increased the activities of SOD and GPX in wheat under drought conditions by promoting the expression of *TaSOD1* and *TaGPx1-D*, which indicate enhanced reactive oxygen species (ROS) scavenging [16].

ROS scavenging genes are antioxidant genes that neutralize ROS accumulated during drought, enabling photosynthetic and cellular recovery. Overexpression of *TaEXPA2*, activated by the MYB transcription factor of wheat named *TaMPS* through promotor binding, enhanced the antioxidant capacity in wheat plants by increasing antioxidant enzyme activity and the increase of the transcripts of some ROS scavenging enzyme-related genes. *TaEXPA2* also positively affected lateral root formation under drought conditions [7]. The wheat *TaZFP13D* gene, encoding Zinc Finger Protein 13D, improves drought tolerance by regulating genes related to oxidative stress, including key ROS producers during photosynthesis [17]. Overexpression of the wheat F-box protein *TaFBA1* enhanced antioxidant capacity, maintained stomatal opening, and reduced water loss [18].

Transcription factors regulate various stress responses, including interactions with ROS and ABA signaling pathways. They modulate drought tolerance mechanisms, influencing either by enhancing or reducing drought stress tolerance.

Overexpressing *TaWRKY31* enhances antioxidant enzyme activities SOD, POD, and CAT, decreased levels of MDA and ROS, and activates stress-response gene expression. Plants exhibited reduced stomatal opening and longer roots under drought treatment indicating that *TaWRKY31* improves drought stress in wheat [19].

Overexpression of the wheat NAC gene (*TaNAC071-A*) significantly enhanced drought tolerance through improved water-use efficiency and increased expression of stress-responsive genes [20]. TaNAC48 increased sensitivity to ABA by mediating crosstalk between the ABA signaling pathway and drought stress responses in wheat, *TaAREB3* binds to cis-acting ABA-responsive element (ABRE). Overexpression of *TaNAC48* significantly improved drought tolerance by increasing proline content, decreasing water loss, malondialdehyde (MDA), and $H_2O_2$ and $O_2$ content [21].

Overexpression of wheat MYB gene *TaMpc1-D4* which is involved in proline biosynthesis reduced proline content remarkably, and decreased POD, SOD, and CAT activities. Moreover, it downregulated P5CS1, RD29A, RD29B, DREB2A, ABF3, CBF1, CBF2, CBF3, ERF1 genes indicating that *TaMpc1-D4* negatively affecting drought tolerance [22].

Squamosa promoter binding protein-like (SPL) transcription factors have a critical role in regulating plant response to different stresses. *TaSPL6-A* gene overexpression in wheat increased water loss, ROS, MDA contents, and decreased ROS scavenging genes indicating that *TaSPL6-* is a negative regulator for drought stress in wheat [23].

*AtSHN1* overexpression enhanced wheat drought tolerance by increasing surface wax reducing water loss [11].

The *TaNHX2-TaGAD1* module enhances drought tolerance, as *TaNHX2* (potassium/proton exchanger) targets the inhibitory domain of TaGAD1 (key enzyme for Synthesizing γ-Aminobutyric acid (GABA) acid from glutamate) thus, mediating crosstalk between the stomatal aperture and GABA (γ-Aminobutyric acid) accumulation. This positively regulates wheat drought stress by affecting plant stomatal movement mechanism [24].

*TaXTH17* a member of the xyloglucan endotransglucosylase/hydrolase (XTH) family which is a cell wall modifying enzyme was found to play a negative role in plant resistance to drought stress [25].

## 3. Heat

Heat stress is an important factor that limits crop productivity, particularly when extreme temperatures occur at plant growth stages as for cereal. It causes morphological, physiological, and biochemical changes.

### 3.1 Impacts of heat stress on wheat

Heat stress accelerates developmental rates and shortens the crop cycle, reducing the expression of leaf area and leading to chlorosis during grain filling. Reduced leaf area and chlorophyll levels lower growth rates and yield. High temperatures affect grain size, grain protein content (GPC), and other quality parameters. At the molecular level, heat stress increases ROS production, and reduces antioxidant enzymatic activity, this way it triggers ROS-induced oxidative injury, such as lipid peroxidation and membrane leakage.

Moreover, heat stress, particularly terminal heat exceeding 30–35°C, can reduce wheat yield by up to 20–40% during the grain-filling stage due to accelerated senescence and impaired photosynthesis. High temperatures reduce grain size, protein content, and overall quality, underscoring the need for heat-tolerant varieties to ensure crop productivity under rising global temperatures. Also, terminal heat affects pollen viability, fertilization, and kernel development, it shortens the grain-filling period by accelerating senescence and reducing nutrient translocation, resulting in smaller grains, lower grain weight, and ultimately reduced yield [26–32].

### 3.2 Heat tolerance mechanisms

Plants employ a range of mechanisms for heat stress tolerance including short-term mechanisms of avoidance or acclimation and/or long-term mechanisms to survive and adapt to heat stress, thermo-tolerance is one of the heat tolerance mechanisms to protect photosynthesis under heat stress. In addition, plants can avoid heat wave damage by increasing both stomatal conductance and transpiration rates, thereby enhancing leaf cooling. Under heat stress, plants with appropriate water supply maintain open stomata for enhancing leaf cooling through transpiration, while under water scarcity plants close their stomata to avoid excess water loss resulting in increased leaf temperature. Thus, mechanisms to heat stress tolerance can be categorized into physiological, biochemical, and molecular responses.

#### *3.2.1 Physiological mechanisms*

- Stomatal regulation: Heat stress triggers stomatal closure to reduce water loss. However, this can limit cooling through transpiration.

- Canopy temperature maintenance: Heat-tolerant plants maintain lower canopy temperatures by optimizing leaf orientation, wax deposition, and cuticle thickness.

- Stay-green trait: Delays leaf senescence, ensuring photosynthesis continues during grain filling under heat.

*3.2.2 Biochemical mechanisms*

- Osmolyte accumulation: Compounds like proline, glycine betaine (GB), and sugars stabilize proteins, protect membranes, and maintain osmotic balance.

- Reactive oxygen species (ROS) scavenging: Enhanced antioxidant enzyme activity mitigates oxidative damage caused by heat stress.

*3.2.3 Molecular mechanisms*

- Heat shock proteins (HSPs): Heat shock proteins (HSPs) play a crucial role in maintaining protein stability, preventing denaturation, and activating stress-response pathways. HSPs act as molecular chaperones to stabilize and refold damaged proteins. Families like HSP70 and HSP90 play crucial roles in stress tolerance, their expression is regulated by heat shock factors (HSFs) that activate stress-responsive genes. Wheat activates stress-associated proteins, including HSPs and antioxidants, which mitigate oxidative damage and protect cellular functions. HSPs like Hsp70 and Hsp17 act as molecular chaperones, stabilizing and refolding denatured proteins during heat stress.

- Heat shock factors (HSFs): HSFs regulate HSP gene expression and help maintain cellular homeostasis.

- Reactive oxygen species (ROS) antioxidants: Heat stress triggers oxidative stress in wheat due to the overproduction of reactive oxygen species (ROS), such as hydrogen peroxide ($H_2O_2$) and superoxide anions ($O_2^-$). These ROS can damage proteins, lipids, and nucleic acids, leading to reduced growth and productivity. To combat this, wheat employs a robust antioxidant defense system, classified into enzymatic and nonenzymatic antioxidants, which are critical for maintaining cellular homeostasis under high temperatures.

Enzymatic antioxidants are the first line of defense against ROS and are crucial for detoxifying harmful by-products of oxidative stress. They can be classified as: follows: Catalase (CAT): Breaks down $H_2O_2$ into water and oxygen, ensuring cellular protection under severe heat stress. Its activity increases proportionally with stress intensity. Glutathione Peroxidase (GPX): Plays a pivotal role in $H_2O_2$ detoxification, safeguarding the photosynthetic apparatus. Superoxide Dismutase (SOD): Converts the superoxide anion ($O_2^-$) into $H_2O_2$, which is further processed by CAT and GPX. Ascorbate Peroxidase (APX) and Peroxiredoxins (Prx): Enhance the elimination of peroxides, reinforcing the antioxidant network. Thioredoxins (Trx): Maintain redox homeostasis by regulating thiol-disulfide interactions.

Nonenzymatic antioxidants complement enzymatic defenses by neutralizing ROS directly and preventing their formation. They include: Phenolic Compounds: Act as key players in scavenging ROS and reducing oxidative stress. Polyphenols: Serve as additional safeguards, preventing auto-oxidation and cellular damage.

- Cell wall modifications: Genes like cellulose synthase-like (Csl) and xyloglucan endotransglucosylases (XTHs) contribute to cell wall elasticity and integrity under heat [31–34].

The expression of 10 heat-responsive genes associated with heat shock proteins (sHsp-1, Hsp17, and HsfA4), flavonoid biosynthesis (F3′-1 and PAL), β-glucan synthesis (CslF6 and CslH), and xyloglucan metabolism (XTH1, XTH2, and XTH5) resulted in significant increase in the relative fold expression with increasing temperature indicating their involvement in providing heat stress tolerance (**Figure 2**) [31].

*TaHSP17.4* and *TaHOP* are key players in stress tolerance mechanisms. Overexpression of these proteins improved tolerance to drought, salinity, and heat stress, by inducing stress-responsive genes related to ROS scavenging and ABA signaling, and by reducing oxidative damage (lower malondialdehyde levels), thus increasing proline content [35].

The heat shock transcription factor gene *TaHSFA6e* undergoes alternative splicing in response to heat stress, producing two major functional transcripts: *TaHSFA6e-II* and *TaHSFA6e-III*. *TaHSFA6e-III* has a 14-amino acid variation that enhances its transcriptional activity compared to *TaHSFA6e-II*, leading to greater upregulation of heat shock protein genes (e.g., *TaHSP70s*). Knockout mutants of *TaHSFA6e* and *TaHSP70s* exhibit increased sensitivity to heat, confirming their critical roles in heat stress tolerance. Heat shock proteins localize in stress granules, aiding in mRNA stabilization and translation reinitiation during recovery from heat stress [36].

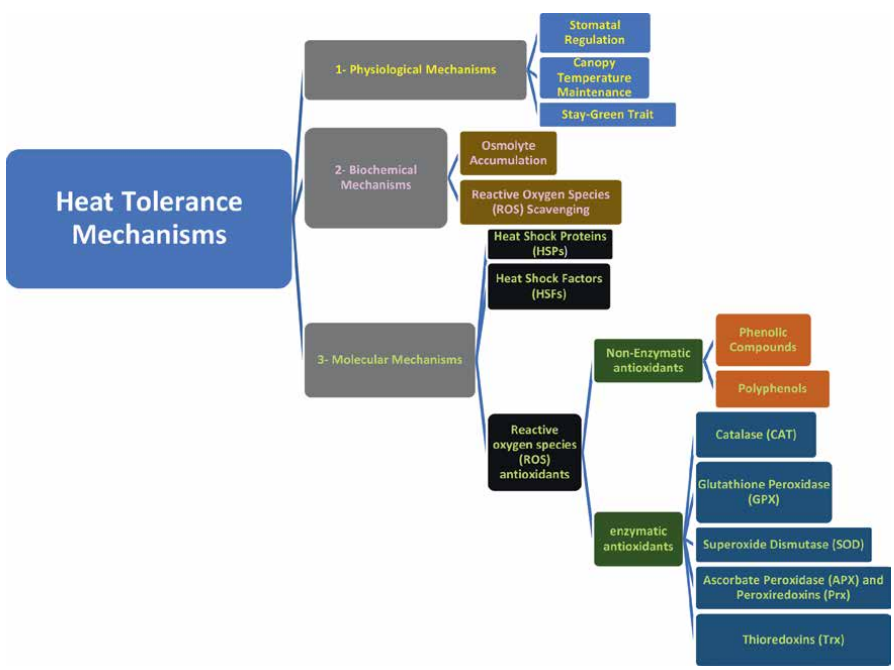


**Figure 2.**
*Heat tolerance mechanisms.*

The heat shock transcription factor HSFA2h regulates the expression of sHSP-17 (a small heat shock protein). Under heat stress, plants overexpressing HSFA2h displayed higher expression of sHSP-17 and enhanced thermos tolerance. The improved tolerance is linked to increased activity of antioxidant enzymes (e.g., SOD, CAT, GPX) and higher total antioxidant capacity under heat stress [37].

Wheat, combined drought and heat stress have more severe effects on the rates of growth and development, as well as photosynthetic rate, stomatal conductance, and chlorophyll fluorescence, compared to the effect of individual stress. Heat stress adaptations in wheat plants rely heavily on activating heat stress-sensitive transcription factors, heat shock proteins (HSPs), and ROS scavenging capacity.

### 3.3 Connection between heat and drought tolerance mechanisms

Both heat and drought stresses often co-occur, especially in arid and semiarid environments. Consequently, plants exhibit overlapping mechanisms to address these stresses such as stomatal regulation: Both stresses trigger stomatal closure to conserve water and reduce transpiration. Osmolyte accumulation: Proline, GB, and sugars accumulate in response to both stresses, stabilizing cellular structures and maintaining osmotic balance. ROS scavenging: Antioxidant enzymes like SOD and CAT are activated to manage oxidative stress caused by heat and drought. HSPs and HSFs: Heat shock proteins and their regulators protect cellular components under both stresses. There is also a Molecular Crosstalk as Abscisic Acid (ABA): A key hormone in drought response, ABA also regulates stomatal closure and stress-responsive gene expression under heat stress. Transcription factors: Shared transcription factors, such as drought-responsive element binding proteins (DREB) and NAC, are involved in both heat and drought tolerance (**Figure 3**) [31, 38–42].

However, there are key differences between heat and drought tolerance mechanisms as indicated in the following **Table 1**.

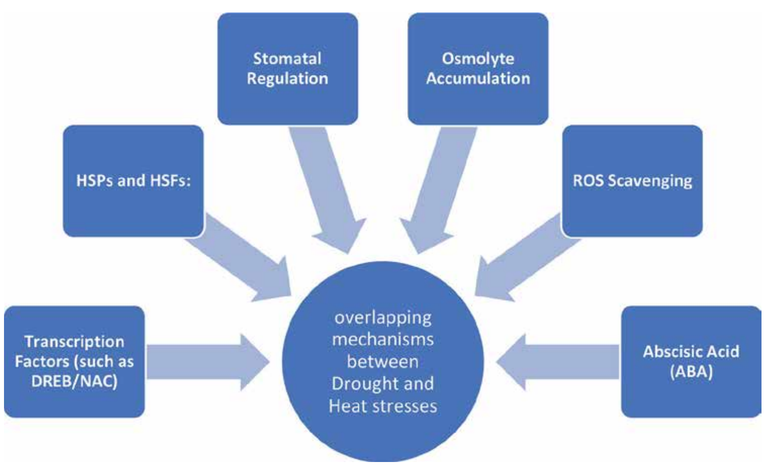


**Figure 3.**
*Connection between heat and drought tolerance mechanisms.*

| Aspect | Heat tolerance | Drought tolerance |
|---|---|---|
| Primary Stress | High temperatures cause protein denaturation and membrane destabilization. | Water deficit reduces turgor pressure and disrupts nutrient transport. |
| Cooling Mechanism | Relies on transpiration cooling and heat dissipation *via* HSPs. | Prioritizes water conservation through stomatal closure. |
| Hormonal Regulation | Primarily regulated by ethylene and HSFs, alongside ABA. | Dominated by ABA, which mediates water-saving responses. |
| Cell Wall Dynamics | Enhanced elasticity to withstand heat-induced expansion. | Reinforcement to prevent collapse under dehydration. |
| Photosynthesis Impact | Damaged chloroplasts reduce photosynthesis directly. | Reduced photosynthesis due to limited $CO_2$ availability. |

**Table 1.**
*Key differences between heat and drought tolerance mechanisms.*

## 4. Salinity

### 4.1 Salinity damaging effects

Salinity is an abiotic stress that severely impacts wheat growth and reduces its productivity. Globally, Salinity stress affects approximately 20% of irrigated lands and 33% of agricultural lands globally, severely impacting wheat productivity. Excess sodium ions reduce water uptake, impair nutrient balance, and decrease grain yield by up to 50% in highly saline soils, emphasizing the critical need for salinity-tolerant wheat varieties to maintain productivity. The primary effects of salt stress are ionic toxicity caused by excess sodium and chloride ions, which disrupt cellular homeostasis, and osmotic stress which reduces water uptake by plants. These factors lead to nutrient imbalance, decreased nutrient availability, and impaired physiological and biochemical functions. Salinity severely reduces seed germination, root elongation, and ultimately grain yield. Furthermore, modifies soil properties including texture and porosity leading to reduced water uptake by plants [43–46].

### 4.2 Salinity coping mechanisms

Salinity tolerance in wheat is a critical factor for growing in areas with high soil salinity. Wheat is sensitive to salt stress, especially during its early growth stages, but it has developed some mechanisms to cope with it. These mechanisms include: (1) Osmotic adjustment plants accumulate compatible solutes (osmolytes) like proline, glycine betaine, and sugars to maintain cell turgor and water uptake under osmotic stress caused by salinity, (2) Ion homeostasis where plants regulate the ion transport to prevent toxic accumulation in cells. This includes sequestering $Na^+$ into vacuoles or excluding it from roots to maintain cellular function, and (3) Antioxidant defense systems salinity induces oxidative stress generating reactive oxygen species (ROS) plants activate antioxidant enzymes such as SOD, CAT, and POD to mitigate oxidative damage, (4) Maintaining $K^+/Na^+$ balance which is critical for enzyme activities and cellular functions, this involves specific transporters such as HKT1, SOS1 to retain $K^+$ and exclude $Na^+$.

### 4.3 Salinity-stress responsive genes

#### *4.3.1 Ion transporters and antiporters*

NHX gene family encodes vacuolar antiporters crucial for managing ion homeostasis under salt stress. The expression of *TaNHX1* and *TaNHX2* genes upregulate under salt stress suggesting their critical role in vacuolar $Na^+$ sequestration, which is necessary to alleviate ionic toxicity. These genes facilitate the sequestration of $Na^+$ into vacuoles reducing cytosolic sodium levels and preventing toxicity. Under salt-stress conditions, upregulation of NHX-$Na^+/H^+$ antiporter activity fueled by the electrochemical proton gradient in the vacuole sap that $H^+$-ATPase creates helps reduce $Na^+$ toxicity through restricting $Na^+$ presence to the vacuole [47, 48].

$Na^+$ movement inside the plant is controlled and regulated by a high-affinity potassium transporter (HKT). HKT transporters are essential for reducing $Na^+$ toxicity and ensuring proper $K^+$ availability, both of which are critical for cellular function under salt stress. HKT transporters function as $Na^+$ selective uniporters, playing a crucial role in regulating $Na^+$ transport to shoots through the xylem vessels by unloading the ion from the xylem in the root into the xylem parenchyma, inhibiting $Na^+$ delivery to the shoot tissues. When $Na^+$ accumulates in the shoot, HKT loads $Na^+$ into shoot phloem cells to be transferred back to the roots through the downward stream. In wheat, *TaHKT1; 5-D* significantly improve salinity tolerance by reducing $Na^+$ accumulation in leaves. Combining HKT-mediated ion transporter with other stress tolerance pathways, such as NHX and SOS systems, can further improve plant resilience to salinity [45, 48].

#### *4.3.2 Transcription factors*

Role of transcription factors in salt tolerance:

Transcription factors (TFs) regulate gene expression by binding to specific promoter regions, enabling plants to adapt to salinity stress. Transcription factors regulate broader stress responses, including osmotic adjustment, ROS detoxification, and gene activation through hormone pathways (e.g., ABA), they are key players in long-term plant adaptation to salt stress.

Key TF families: (1) AP2Ethylene Response Factor (ERF) includes DREB/CBF subfamily, which regulates genes with dehydration-responsive elements (DRE/CRT) as in DREB2 which enhances salt tolerance by regulating osmotic stress-responsive genes. (2) NAC where wheat *TaNAC69* promotes salt stress tolerance by activating downstream stress-responsive genes involved in ion transport and osmotic adjustment. (3) bZIP (Basic Leucine Zipper) these TFs regulate ABA-dependent pathways, *TabZIP6* and *TabZIP13* in wheat modulate ABA-responsive genes, contributing to salt stress resilience. (4) WRKY plays a dual role in abiotic and biotic stresses by binding to W-box elements in target promoters. *WRKY33* enhances salt tolerance by controlling ROS detoxification pathways. (5) MYB transcription factors regulate flavonoid pathways and stress-responsive genes, *TaMYB32* and *TaMYB73* in wheat are upregulated under salinity, supporting osmotic balance and antioxidant defense, the overexpression of *TtMYB1* into transformed wheat, enhances proline and soluble sugar levels while reduces malondialdehyde levels suggesting improve salinity tolerance in wheat [43, 49].

#### *4.3.3 ROS defense mechanisms*

Overexpressing *TaCHP* (Calcium-binding protein) enhances plant antioxidant capacity by activating SOD, CAT, and POD enzymes, stably enhancing wheat yields under salt-stress conditions indicating the potential of this gene for improving salt tolerance in wheat [49].

#### *4.3.4 Epigenetics*

Adenine methylation acts as an epigenetic regulator of *SSADH* gene during salt stress. *SSADH* gene plays a significant role in salt tolerance by regulating the GABA shunt, which helps control ion homeostasis, ROS detoxification, and energy metabolism under stress conditions. Increased methylation of specific promotor sites enhances transcriptional activation, helping the adaptive response of wheat to salinity [50].

#### *4.3.5 Salt overly sensitive (SOS) pathway*

The SOS pathway is a crucial signaling mechanism in plants that helps coping high salinity in the environment. This pathway is primarily involved in regulating sodium ($Na^+$) and potassium ($K^+$) ion balance to reduce the detrimental effects of $Na^+$ toxicity in plant cells. SOS pathway also interacts with other stress-response pathways, such as (1) The NHX and HKT transporter systems, the increased $Na^+$ efflux through SOS1 can complement the $Na^+$ sequestration into vacuoles through NHX transporters, thus

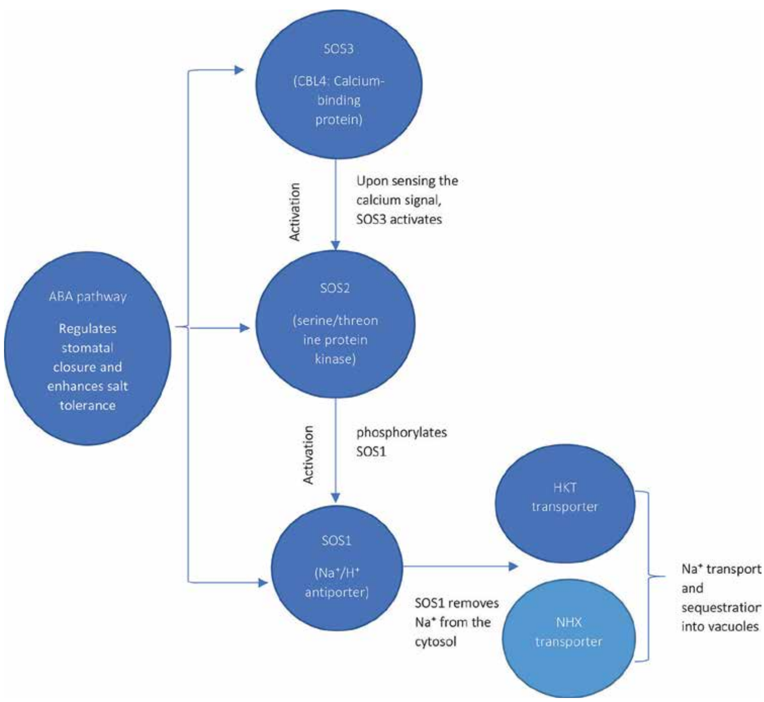


**Figure 4.**
*SOS pathway for salinity tolerance.*

| Gene/Pathway | Function | Mechanism |
|---|---|---|
| NHX ($Na^+/H^+$ Exchangers) | Sequesters $Na^+$ into vacuoles to reduce cytosolic $Na^+$ toxicity. | Vacuolar compartmentalization of $Na^+$ using proton gradients created by $H^+$-ATPases and $H^+$-PPases. |
| HKT (High-Affinity Potassium Transporters) | Reduces $Na^+$ accumulation in shoots and maintains $K^+/Na^+$ balance. | Retrieves $Na^+$ from xylem sap and returns it to roots *via* phloem. |
| Salt Overly Sensitive (SOS) Pathway | Regulates $Na^+$ efflux and ensures $K^+$ homeostasis. | SOS1 ($Na^+/H^+$ antiporter) removes $Na^+$; SOS2 (kinase) and SOS3 (calcium-binding protein) activate this process. |
| Transcription Factors (e.g., DREB, WRKY, NAC) | Regulate expression of stress-responsive genes. | Activate genes for osmotic adjustment, ROS detoxification, and ion homeostasis. |
| *TaCHP* (Calcium-Binding Protein) | Enhances antioxidant capacity and stabilizes yields under stress. | Activates SOD, CAT, and POD enzymes for ROS scavenging. |
| Epigenetics (e.g., SSADH) | Regulates ion homeostasis and stress tolerance through transcriptional activation. | Adenine methylation increases the expression of genes like SSADH in response to salinity. |

**Table 2.**
*Key genes involved in wheat tolerance to salinity and their mechanisms.*

working synergistically to reduce overall $Na^+$ toxicity. (2) ABA, which is involved in regulating stomatal closure and other drought responses. The integration of these pathways contributes to the overall salt tolerance of plants.

The key components of this pathway SOS1, SOS2, and SOS3 coordinate to maintain $Na^+$ homeostasis: (1) SOS1: A plasma membrane $Na^+/H^+$ antiporter responsible for removing excess $Na^+$ from the cytosol, it is activated by phosphorylation through the SOS2 kinase. This step is critical for reducing $Na^+$ accumulation in root cells and minimizing its transport to shoots. (2) SOS2: serine/threonine protein kinase that acts as the central mediator of the SOS pathway, when activated by SOS3, it phosphorylates and activates SOS1 to enhance $Na^+$ efflux. (3) SOS3 (CBL4): A calcium-binding protein that senses cytosolic $Ca^{2+}$ changes triggered by salt stress, it interacts with SOS2 to form a kinase complex, guiding the activation of SOS1 (**Figure 4**, **Table 2**) [44].

## 5. Genome editing for improved abiotic stress tolerance

Wheat being a staple crop worldwide is severely affected by abiotic stress, as it affects plant growth and crop yield, limits agricultural productivity, influences key physiological processes like photosynthesis and cell growth, and leads to metabolic changes. Thus, improving its resilience to abiotic stresses such as drought, salinity, and heat stress is crucial for ensuring food security under changing climatic conditions. Genome editing has emerged as a transformative technology in agricultural research, with the ability to enable precisely targeted modifications in plant genomes for crop enhancement to address the challenges of global food security and environmental sustainability. Transcription Activator-Like Effector Nucleases (TALENs) are another powerful genome-editing tool for enhancing wheat's resilience to abiotic stresses. They can be effectively utilized in various crops to enhance

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resilience against abiotic stresses. In rice, TALENs have been employed to modify genes such as *OsPDS, OsBADH2, and OsMPK2*, which are involved in responses to abiotic stress, as well as the genes *TaMLO-A1*, *TaMLO-B1, TaMLO-D1* in wheat to improve resistance to powdery mildew (biotic stress) [51]. These applications demonstrate the potential of TALENs in improving crop resilience to environmental stresses. While specific examples in wheat are limited, the successful use of TALENs in other crops provides a foundation for future research aimed at enhancing wheat's tolerance to abiotic stresses.

This section focuses on the advancements and applications of genome editing technologies, particularly (Clustered Regularly Interspaced Short Palindromic Repeats) CRISPR-Cas systems, in improving wheat tolerance to abiotic stresses.

Engineering transcription and signaling factors as a strategy for improving plant stress tolerance could develop robust, abiotic stress-tolerant crops, but challenges remain in understanding regulatory mechanisms and achieving stable field performance. Transcription factors (TFs) are master regulators in stress responses, modulating the expression of multiple genes. Families such as Dehydration Responsive Element Binding (DREB), basic leucine zipper (bZIP), MYB, and NAC are commonly engineered for drought tolerance. Overexpressing TFs like *DREB1A* improves drought tolerance by enhancing traits such as water-use efficiency, yield, and stress-related protein expression. Moreover, Signaling Factors (SFs) regulate plant stress responses through pathways involving calcium sensors (e.g., CBL-CIPK systems) and kinases (e.g., MAPKs, SnRKs). Engineering these pathways improves drought tolerance by enhancing water retention, oxidative stress protection, and signal transduction, including examples such as *TaSnRK2.9* in wheat, which improves stress resistance and physiological traits. Advances in tools like synthetic zinc-finger proteins enhance the efficiency of gene activation or repression [52].

CRISPR/Cas9-mediated genome editing can be used to target abiotic stress-related genes for overexpression to enhance their function and improve abiotic stress tolerance such as; *TaCER1–6A*, *TaHAG1*, *TaPGK* which are related to drought (Overexpression increased wax alkane levels, reducing water loss and improving drought tolerance), salinity (Overexpression improved antioxidant activity, ionic balance, and salinity tolerance), and cold (Overexpression enhanced energy metabolism, reducing cellular damage under cold stress) receptively. It can also be used to knockout genes to remove their activity and study their role in stress responses or eliminate undesirable traits such as *TaCER1–6A*, *TaHAG1, TaHSFA6e, TaHSP70, TaPGK, TaPHT1;9* that are related to drought (Knockout reduced wax alkane levels, leading to increased water loss and reduced drought tolerance), salinity (Knockout reduced antioxidant activity, increased $Na^+$ levels, and diminished salinity tolerance), heat (heat shock transcription factor Knockout reduced survival rates under heat stress), cold (Knockout reduced energy metabolism, increasing cellular damage and cold sensitivity) and heavy metals (phosphate transporter Knockout reduced arsenic uptake and improved growth under arsenic stress) respectively [53].

CRISPR/Cas9-mediated genome editing can also be used to study gene function, for example the Overexpression of DIW1 gene (*TaPP2C158*) showed drought-sensitive phenotypes with faster water loss and higher leaf rolling index (LRI), reduced stomatal closure under drought, leading to increased water loss. While Knockout mutants created using CRISPR/Cas9 displayed improved drought tolerance, including lower LRI and reduced water loss. Suggesting that DIW1 gene (*TaPP2C158*) negatively regulates drought tolerance in wheat [54].

| Feature | CRISPR | TALENs |
|---|---|---|
| Targeting | Requires a PAM sequence near target site | No PAM requirement, highly customizable |
| Specificity | High but may have off-target effects | Very high with minimal off-target effects |
| Ease of Design | Easier and faster to design | More labor-intensive (protein engineering) |
| Cost | Relatively low | Higher due to design complexity |
| Applications | Widely used for multiplex editing | Preferred for challenging targets (e.g., no PAM site) |
| Editing Mechanism | Uses RNA-guided DNA cleavage | Uses protein-DNA binding for specificity |

**Table 3.**
*Comparison between CRISPR-Cas9 and TALENs.*

Targeting root system architecture (RSA) *TaRPK1* gene which is a receptor-like protein kinases involved in abiotic stress responses with CRISPR/Cas9-mediated genome mutagenesis achieved 41.93% mutation efficiency, increased root length, depth, surface area, and volume leading to improved root traits contributed to better water and nutrient uptake [55].

In conclusion, genome editing has a great potential for enhancing wheat's tolerance to abiotic stresses through the following:

1. Precise modification of stress-related genes: Including techniques such as overexpression, knockout, and targeted mutations to directly influence genes that play key roles in stress responses.

2. Functional analysis of genes linked to abiotic stress tolerance: Genome editing enables the study of gene functions, offering insights into how specific genes contribute to wheat's resilience under challenging environmental conditions.

To understand the suitability of different genome-editing tools for improving wheat tolerance to abiotic stresses, the following **Table 3** compares CRISPR-Cas9 and TALENs in terms of their applications, efficiency, and challenges.

## 6. Challenges and future prospects of genome editing

Genome editing offers a promising and sustainable solution for addressing food security by enhancing crop tolerance to abiotic stresses, such as drought, heat, and salinity, under changing climate conditions. While plants developed using these strategies have shown promising results, most studies have been conducted in controlled environments, with limited field trials to assess their real-world performance. Therefore, a better understanding of complex regulatory networks and more extensive field testing are required to develop these plants into high-yield, stress-tolerant crops able to address the food gap. Combining genome editing with other biotechnological tools, such as marker-assisted breeding and transcriptomics, could open up new possibilities for improving wheat's stress resistance. Additionally, advancements in CRISPR technologies, including multiplex editing, hold great promise for making more precise and comprehensive changes to complex traits.

## 7. Policy implications of enhancing wheat resilience

The increasing frequency and intensity of abiotic stresses, driven by climate change, presents a severe threat to global food security. Wheat, as one of the world's staple crops, is particularly vulnerable to drought, heat, and salinity stresses, causing significant yield losses annually. To address these challenges, an integrating innovative solutions such as genome-editing technologies are required, to be incorporated into agricultural policies and practices. Enhancing wheat resilience ensures stable and increased production under stressful environmental conditions.

By reducing the yield losses caused by abiotic stresses, stress-tolerant wheat varieties contribute to ending hunger and improving nutrition, particularly in regions heavily reliant on wheat for sustenance achieving SDG 2: Zero Hunger. Besides, developing wheat varieties that can adapt to drought, heat, and salinity directly supports climate change adaptation strategies. These advancements mitigate the negative impacts of extreme weather events, ensuring food security in the face of global warming to fulfill SDG 13: Climate Action.

## 8. Policy recommendations

To maximize the impact of genome editing and other advancements for improving wheat resilience to abiotic stresses, the following policy measures are recommended:

1. Research funding: Increasing investment into genome-editing technologies, such as CRISPR-Cas9, as they can accelerate the development of stress-tolerant wheat varieties.

2. Collaboration and knowledge sharing: Promote international partnerships between research institutions, policymakers, and private sectors to share knowledge, tools, and best practices in wheat improvement.

3. Capacity building: Training programs for scientists and breeders on genome-editing techniques can help integrate these tools into breeding programs worldwide.

4. Regulatory frameworks: Simplifying the approval processes for genetically edited crops while maintaining safety standards can encourage innovation and adoption.

5. Focus on climate-resilient agriculture: Integrate wheat genome-editing initiatives into broader climate adaptation policies, aligning with Sustainable Development Goals 2 (Zero Hunger) and 13 (Climate Action).

6. Public awareness and acceptance: Educate stakeholders, including farmers and consumers, about the benefits and safety of genome-edited crops to enhance acceptance and adoption.

## 9. Future directions

As wheat resilience improves through genome-editing advancements, future research should focus on:

- Expanding the understanding of stress-response pathways and identifying new stress-related genes.
- Conducting field trials in diverse agroecological zones to ensure the adaptability of edited wheat varieties.
- Exploring multi-stress tolerance to address combined stresses, such as heat and drought, simultaneously.

By incorporating these policy measures and aligning scientific advancements with global goals, we can pave the way for a resilient, sustainable, and secure wheat production system capable of feeding a growing global population under changing environmental conditions.

## 10. Conclusion

Addressing abiotic stresses such as drought, salinity, and heat is critical for ensuring better wheat productivity and global food security in the face of climate change and a growing global population. This chapter highlights the molecular mechanisms underlying stress tolerance and the transformative potential of genome-editing technologies, including CRISPR-Cas9 and TALENs, in enhancing wheat resilience.

The integration of advanced genetic tools into wheat improvement programs offers a sustainable and efficient approach to developing multi-stress-tolerant varieties. These technologies can significantly mitigate yield losses, improve resource efficiency, and support the transition to climate-resilient agriculture.

Future research should focus on exploring stress-response networks at the molecular level, encouraging editing for multi-stress tolerance, and conducting extensive field trials to validate the performance of edited varieties under real-world conditions. Furthermore, aligning scientific advancements with supportive policies and public engagement will be essential to maximize the impact of genome editing on agricultural sustainability and food security.

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Chapter 3

# Plant Disease Resistant in the Triticum

*Abdulkreem Alsalmo, Tareq Hamijo, Mukaddes Kayim and Ahmad Al-Mourrh*

## Abstract

Wheat, a global food security crop as well as a source of livelihood, is essential to global food security. Nonetheless, its production has been threatened by biotic stresses, particularly fungi-form diseases being a big hindrance to yield since it reduces the annual yield by over 62 million metric tons worldwide. Some of these diseases include leaf rust, stem rust, stripe rust, and Fusarium head blight, among others, and these affect developed as well as developing worlds economically and socially. These risks can be managed by the Integrated Disease Management (IDM) approach that deals with genetic resistance, cultures, and chemical and biological treatments. However, there are challenges associated with IDM: pathogen development, fungicide resistance, and how climate change affects pathogen-host relationships. New knowledge in molecular genetics and plant pathology has led to the discovery of many QTLs and resistance genes and the possibility of developing new adapted wheat varieties. Novel enabling technologies like CRISPR, gene editing, and high-throughput omics tools have a fast-paced change in resistance breeding, but genetic and crop context are key to the durability and effectiveness of resistance sources. To ensure sustainable wheat production and global food security, significant investments in research and development are crucial. This includes advancing pathogen surveillance, accelerating the deployment of molecular breeding technologies, and promoting farmer education programs to implement IDM strategies effectively. Collaborative global efforts must prioritize the development of climate-resilient, disease-tolerant wheat varieties to address current and emerging challenges.

**Keywords:** wheat, pathogen, hypersensitive response, enzymes, genomic selection and breeding

## 1. Introduction

As one of the four foundational crops in the world, wheat plays a significant role in underpinning food security and providing the capacity for billions of people to earn their livelihood. It is also critically important to the world's food supply not only as a major source of a portion of humanity's total daily calorie intake but also as part of animal feed and non-food industrial uses [1, 2]. Nevertheless, wheat production is in growing danger from a variety of biotic stresses that include over one hundred diseases that can be both costly and socially disruptive. Annual yield cuts in the United States can increase up to 20%, mainly attributed to pathogenic agents for leaf rust, stem rust, stripe rust (**Figure 1A**), Fusarium head blight, and powdery mildew (**Figure 1C**), just to name a few in bacterial, viral, and fungal diseases [3, 4]. Such losses not only influence the productive levels of agricultural systems and their revenues but also intensify the problem of the world's hunger. Integrated Disease Management (IDM) has been developed as the key approach to address all these challenges through the use of genetic resistance, chemical and biological controls, and cultures. Of the available resistance strategies, genetic resistance is widely regarded as the first, most effective, sustainable, and cost-efficient means of controlling diseases [3]. However, IDM's pragmatic application falls on significant challenges such as the emergence of more virulent aggressive pathogen strains, rising cases of fungicide resistance, as well as the interaction of complex effects of climate change on disease dynamics and pathogen host-parasite relationships [5]. A plethora of quantitative trait loci (QTLs) and resistance genes have been identified in modern plant pathology and molecular biotic wheat genetics, enabling the understanding of the wheat-pest disease relationship in light of advanced techniques and genetics. Such findings have great potential in selecting higher disease tolerance and climate change tolerance germplasm for future wheat improvement programs.

To date, fungal pathogens have been reported to be the most threatening biotic constraint in wheat-growing WA, and it is alarming that approximately 90% of the world's wheat-growing areas are vulnerable to diseases like stem rust, stripe rust (**Figure 1A**), leaf rust, Fusarium head blight, and septoria tritici blotch [6]. Combined, they cause an annual yield loss of up to 62 million metric tons, or about 8.5% of the global yield of wheat. These contain long-term consequences, resulting in a caloric deficit with the capacity to impact 173,000,000 individuals every year and lead to economic losses worth $4.2 billion–10.8 billion [3, 7]. By now, it is quite apparent that certain parts of the geographic world are much more exposed to the risks because of propitious climatic conditions and a lack of healthcare facilities to

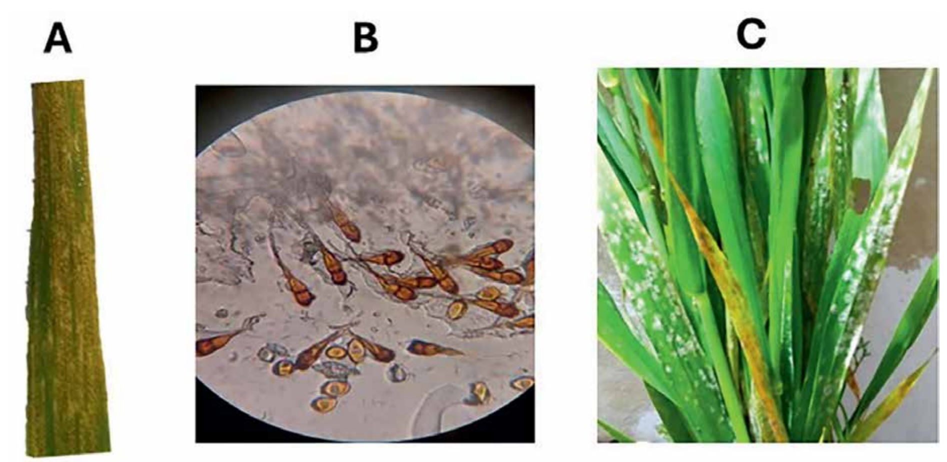


**Figure 1.**
*Stripe rust of wheat (A), teliospores of strip rust (B), and powdery mildew (C).*

contain potential diseases [8]. Even the developed countries that are growing wheat today are not safe from these challenges, and thus, a global problem is in front of us. These biotic threats are alarming; hence, there is so much required investment in the global research and development for the improvement of disease-tolerant wheat varieties, improved infrastructure, epidemiological surveillance, and effective farmer education programs. To address this problem, the annual global investment in Research and Development (R&D) is estimated at $350–974 million, and significant economic and social benefits can be obtained to reduce the impact of diseases on global food security [8, 9]. In order to do this, the development of disease management strategies for specific geographical locations, together with strong pathogen surveillance and efficient, long-term resistance development programs, are required. Such measures are needed not only to protect the crop and boost its yield but also to stabilize world agricultural food production systems facing new climate and ecological conditions [10].

## 2. Genetics of disease resistance in wheat

### 2.1 Basics of plant-pathogen interactions

Thus, unique genetically encoded immune mechanisms in plants do not include a circulatory system and immunity to microbes, while the animal system uses far more flexible adaptive immunity. This immunity exists at the cellular level in the plant organs and at cellular levels throughout the plant body. The foundational framework of plant immunity is built upon a two-tiered defense mechanism: Two of the well-documented forms of defense response include: PAMP-Triggered Immunity (PTI) and Effector-Triggered Immunity (ETI) [11].

The first tier involves PTI, which is triggered when receptors on the plant surface, PRRs, recognize PAMPs, highly conserved molecules required for pathogen viability. Some of the best-illustrated PAMPs are bacterial flagellin and fungal chitin, among many others. Once detected, PRRs trigger a signal transduction pathway that results in defense responses, including the production of reactive oxygen species (ROS), activation of mitogen-activated protein kinase (MAPK) pathways, synthesis of defense-related genes, and cell wall strengthening through callosing. These responses are useful for halting the advancement of a majority of non-scientific sickness-causing microorganisms. However, specific microorganisms can modulate PTI through the use of effector molecules, thus creating effector-triggered susceptibility (ETS) [12].

In response to ETS, plants have developed the second still effective line of defense, that is ETI, controlled by intracellular resistance (R) proteins, many of which represent the Nucleotide-binding Leucine-rich Repeat (NLR) protein family. Depending on the source, these R proteins either directly identify particular pathogen effectors or identify the changes by these effectors on the host targets. NEIn that context, ETI escalates the defense response launched by PTI to enhance immune activation and respond more quickly to the invader. An equally important characteristic of ETI is the hypersensitive response, or HR, a form of cell necrosis designed to confine pathogen proliferation, although the infected and adjacent cells will die [13]. The process of plant-pathogen communication is summarized in the plant immune model known as the zigzag model. This model explains how activation and suppression take turns as plants and pathogens learn from each other. In the first phase, PRRs identify PAMPs leading to PTI and the overall decrease of pathogen load. In the second phase, the successful pathogens translocate effectors to suppress PTI and thus lead to ETS. The third phase involves ETI, wherein R proteins come into play; they can discern the effectors themselves or their activities, and the plant's immunity is restored. Last, pathogens may switch the recognized effectors or even gain new effectors in order to suppress ETI, which results in an ongoing co-evolution [12].

Combined, PTI and ETI are two well-coordinated structures that shape the elaborate and efficient immune system with generalized and specialized immunity. These mechanisms offer valuable information about the recognition of the molecular, signaling, and co-evolution of plants with their diseases. Such knowledge provides the underlying knowledge of ways to improve crop resistance through current genetic techniques and breeding.

## 2.2 Types of resistance

Resistance to pathogens in plants can be put into two groups: major gene resistance and polygenic resistance. Molecular plant resistance is generally controlled by single major R genes that usually involve a dominant resistance against the pathogen. This form of resistance is often race-specific, that is, it acts against specific races of a pathogen and is linked with hypersensitive response (HR), which results in localized death of cells to limit the movement of the pathogen. Polygenic resistance entails the earth of a number of genes that individually have small but cumulative effects qualified as seminal or mild but lengthy-terminus resistance [14]. It is often race non-graphic and offers coverage across multiple pathogen strains with a single formulation. However, it may be a temporary measure because major genes often provide durable resistance; pathogens learn how to overcome it, whereas the polygenic resistance might take longer to develop but is less violent in nature. Using these strategies in breeding programs can improve the efficiency of these two aspects and also the duration of plant resistance [15].

Specifically, the hypersensitive response (HR) is an important component of plant PI, especially in major gene (qualitative) resistance. This is a controlled Programmed cell death (PCD) process that takes place at the site of infection when plant R proteins identify specific pathogen-derived effectors. This rapid cell death sets up a physical and biochemical blockage that slows and contains further pathogen development and spread.

### *2.2.1 Programmed cell death (PCD) in plants*

Apoptosis, or programmed cell death (PCD), is an indispensable and highly controlled phenomenon in plants that plays a key role in plant growth and development, as well as in response to stress. While necrosis is the passive, pathological form of cell death that results from injury or intensive stress, PCD is an activated, endogenous plant cell death [16]. PCD manifests in two primary contexts: ontogeny of physiological and biochemical processes and stress by biotic and abiotic factors. Developmental PCD controls aspects of plant architecture and several other functions, including processes that involve the elimination of cells during xylem formation, endosperm degradation in seeds, and senescing processes in the leaf. In contrast, pathogen-triggered PCD, more relevant to the hypersensitive response (HR), is a controlled pathogen-directed program leading to the death of infected cells to discourage the growth of biotrophic pathogens. This defense is initiated by molecular phenomena such as changes in concentration of calcium ions, generation of ROS, or production of hormones, ethylene, or jasmonic acid for dismantling the next cell. The main participants of PCD are proteases, nucleases, and mitochondria as effectors of cellular degradation and autophagy as degradation with regard to order. PCD is also involved in environmental stress tolerance, including drought, salinity, and UV-B stress responses. The process is tightly regulated by an intricate genetic and molecular network of R genes, transcription factors, and hormones to control the survival of plant cells and their programmed death. Current knowledge of PCD has implications with regard to application in increased crop productivity, greater control over plant growth, and better protection from diseases and other forms of biotic and abiotic stress [17].

#### *2.2.2 Resistance genes (R genes)*

In wheat, Resistance (R) genes are involved in the defense system of plants against pathogens such as fungi and bacteria, viruses, and nematodes. These genes produce proteins that directly identify pathogen-derived effector molecules and then cause a specialized immune reaction called effector-triggered immunity (ETI). R genes may be part of the nucleotide-binding leucine-rich repeat (NLR) family, which acts to recognize and transmit the signal during the pathogen invasion. Wheat, being an important food crop, has been analyzed for its R genes, as the disease resistance is crucial for developing resistance resistant crop varieties [18]. The genetic-engineering tools in the form of genomics and molecular biology have enhanced the identification of cloning of several R genes to give culture of wheat to counter threats such as rust and powdery mildew (**Figure 1A**).

### 2.3 Genetic mapping and identification of resistance genes

Molecular breeding has, for the first time, accurately identified the exact sites in chromosomes that contain genes controlling desirable traits in wheat, such as resistance to diseases. Instead of constructing low-resolution linkage maps, researchers use molecular markers such as single nucleotide polymorphic sites (SNPs) and simple sequences repeats (SSRs) to provide clear patterns of inheritance [19, 20]. This strategy has been used successfully in the past for map-based cloning of resistance genes like Lr34 and Lr67, which are vital for developing durable sources of resistance in wheat.

QTL mapping extends genetic mapping by finding chromosomal regions linked with complex quantitative traits phenotypes that are controlled by multiple genes and environments. This technique also calculates the relative contribution of these regions to other characteristics so desired, such as disease resistance and yield. In wheat, tens of genes and quantitative trait loci (QTLs) behind important traits such as leaf rust resistance have been mapped from hundreds using Genome Wide Association Studies (GWAS) and bi-parental mapping [21].

Marker-Assisted Selection (MAS) takes wheat improvement to another level by identifying molecular markers with defined attributes on the plants. As for the MAS use of genes, it can create such a gene combination at least introgression such favorable genes as resistance to the diseases irrespective of phenotypic characteristics. This process has created varieties for stem rust resistance genes, including Lr34, Lr46, and Lr67, whereby genes are pyramided in a single cultivar and act as a buffer against pathogens [19].

Among all the technology improvements, the transfer and incorporation of resistance genes and QTLs into wheat have had a big impact. The major (qualitative) and polygenic (quantitative) resistance genes coordinated in breeding protect against continually changing pathogens in a broad-spectrum and long-lasting manner. This pyramiding increases the durability of resistance in wheat varieties to a very high level. Today, the global use of the techniques of genetic mapping, QTL analysis, and MAS has greatly impacted wheat breeding programs [22]. These have promoted the creation of resistant cultivars to severe diseases, including leaf rust and powdery mildew, hence enhancing food security in agriculture. Modern instruments have refined practices of selection that are more conducive and accelerated than the previous conventional techniques, and different diseases and climate change issues have been a major concern for breeder selection.

## 3. Mechanisms of disease resistance

### 3.1 Plant immune responses

*3.1.1 Recognition of pathogens*

*3.1.1.1 PAMP-triggered immunity (PTI)*

Entails identification of conserved microbial or pathogen associated molecular patterns (PAMPs/MAMPs) by cell surface localized transmembrane receptors referred to as PRRs [23].

- Example: Flagellin and ELONGATION FACTOR TU (EF-Tu) are sensed by PRRs such as FLS2 and EFR in Arabidopsis. PTI is known to stop the early steps of infection by activating the defense mechanisms molecular patterns (PAMPs/MAMPs) by transmembrane Pattern Recognition Receptors (PRRs).

- Example: Flagellin and elongation factor Tu (EF-Tu) are recognized by PRRs like FLS2 and EFR in Arabidopsis.

- PTI halts early stages of infection by triggering defense responses.

*3.1.1.2 Effector-triggered immunity (ETI)*

- Mediated by intracellular NB-LRR proteins encoded by R genes.

- Recognizes pathogen effectors either directly (via physical interaction) or indirectly (monitoring changes in host targets caused by effectors, as in the "guard hypothesis") [23].

- ETI leads to an enhanced defense response and often triggers a hypersensitive response (HR) to contain the pathogen.

*3.1.1.3 Indirect and direct recognition*

- Indirect: Example includes the Arabidopsis protein RIN4, which is modified by multiple bacterial effectors and subsequently activates NB-LRR proteins RPM1 and RPS2.

- Direct: Interaction between fungal Avr proteins and NB-LRR proteins like those in flax rust [6].

#### *3.1.2 Signaling pathways in plant immunity*

##### *3.1.2.1 PAMP signaling pathways*

Engagement of PRRs activates signaling cascades, including Mitogen-Activated Protein Kinase (MAPK) pathways, leading to transcriptional reprogramming and production of defense molecules [23].

##### *3.1.2.2 ETI signaling pathways*

ETI responses are faster and stronger than PTI, involving reactive oxygen species (ROS) production, salicylic acid accumulation, and transcriptional activation of resistance genes.

Crosstalk between salicylic acid (SA), jasmonic acid (JA), and ethylene (ET) pathways determines the nature of the response based on pathogen type (biotrophs vs. necrotrophs) [24].

##### *3.1.2.3 Systemic responses*

Systemic Acquired Resistance (SAR): Mediated by SA signaling, providing long-lasting immunity throughout the plant [8].

Signal molecules like small RNAs and mobile defense signals play a role in amplifying systemic defense responses [25].

##### *3.1.2.4 Pathogen suppression mechanisms*

Pathogens use effectors to suppress PTI and ETI by targeting key components of the immune signaling pathways, such as MAPK cascades or hormone signaling [26].

### **3.2 Structural barriers (e.g., cell walls, cuticles)**

#### *3.2.1 Structural barriers in plant immunity*

##### *3.2.1.1 Cell wall*

- The plant cell wall serves as a primary structural barrier against pathogen entry.
- During infection, plants reinforce their cell walls by depositing callose, lignin, and other materials to strengthen the barrier at the site of pathogen attack.
- Mutants like pen (penetration-deficient) in Arabidopsis show compromised cell wall defenses, allowing partial pathogen penetration [16].

##### *3.2.1.2 Cuticle*

- The outermost layer of plants, primarily composed of wax and cutin, prevents pathogen adhesion and penetration.
- The cuticle acts as a passive physical barrier to many pathogens, especially fungi and bacteria.

#### *3.2.1.3 Cell wall appositions (papillae)*

- Localized thickening of the cell wall occurs at attempted pathogen entry sites.
- Papillae are enriched with antimicrobial compounds and enzymes, providing a reinforced defense mechanism.

#### *3.2.1.4 Pre-invasion defense mechanisms*

- Components like PEN1 syntaxin and PEN3 ABC transporters are involved in secreting defense-related compounds to the site of pathogen attack.
- The actin cytoskeleton supports the transport of vesicles and other materials required for rapid cell wall reinforcement [27].

#### *3.2.1.5 Extracellular matrix*

- The matrix surrounding the plant cells interacts with pathogens and contributes to defense.
- Haustorial interfaces in biotrophic infections (e.g., by fungi and oomycetes) are tightly regulated to limit pathogen access to host resources.

## 3.3 Biochemical mechanisms (production of enzymes, toxins, etc.)

### *3.3.1 Biochemical mechanisms in plant immunity*

#### *3.3.1.1 Enzyme production*

- *Hydrolytic enzymes*

  Plants produce enzymes like chitinases, glucanases, and proteases to degrade pathogen cell walls (e.g., fungal chitin and glucans) [28].

- *Peroxidases*

  Catalyze the production of reactive oxygen species (ROS) and contribute to cell wall strengthening through lignin polymerization.

- *Lipases*

  Break down lipid components of pathogen membranes, playing a role in direct defense.

#### *3.3.1.2 Toxin production*

- *Phytoalexins*

  Low molecular weight antimicrobial compounds were synthesized in response to pathogen attack [29].

Examples include camalexin in Arabidopsis and glyceollin in soybean.

- *Pathogen-inhibitory proteins*

  Examples include defensins and thionins, which disrupt pathogen membranes or inhibit growth [30].

*3.3.1.3 Hormone-mediated defense responses*

- *Salicylic acid (SA)*

  Accumulates during biotrophic infections and activates systemic acquired resistance (SAR).

  Jasmonic acid (JA) and ethylene (ET)

  Important for defense against necrotrophs and herbivory. JA also represses auxin signaling, reducing pathogen advantage.

- *Abscisic acid (ABA)*

  Modulates stomatal closure to prevent bacterial entry.

*3.3.1.4 Reactive oxygen species (ROS)*

Produced during the oxidative burst, ROS have direct antimicrobial properties and signal the activation of downstream defenses.

*3.3.1.5 Production of secondary metabolites*

- *Alkaloids, Terpenoids, and Phenolics*

  Act as antimicrobials, inhibit pathogen enzymes and contribute to structural defense (e.g., lignification) [31].

- *Flavonoids*

  Serve as antioxidants and defense signals in certain plant-pathogen interactions.

*3.3.1.6 Microbe-associated molecular pattern (MAMP) recognition*

Induces the production of antimicrobial peptides and secondary metabolites upon detection of molecules like flagellin or EF-Tu.

*3.3.1.7 Inhibitors of pathogen effectors*

Example: Tomato Cf-2 protein recognizes the inhibition of Rcr3 protease by the fungal effector Avr2, activating downstream defenses.

*3.3.1.8 Detoxification of pathogen toxins*

Some plants produce enzymes to neutralize pathogen-derived toxins, minimizing damage.

## 4. Breeding techniques, molecular tools, and sustainable disease management

The integration of molecular tools, advanced breeding techniques, and sustainable disease management strategies offers a holistic approach to addressing the persistent challenges posed by wheat diseases. By combining innovations in genetics, biotechnology, and agronomy, it is possible to develop durable and eco-friendly solutions that ensure global food security.

### 4.1 Traditional breeding techniques for resistance

Traditional breeding techniques have been a cornerstone in the development of disease-resistant wheat (*Triticum*) varieties. These approaches focus on selecting and crossing wheat lines with desirable traits to produce offspring with enhanced resistance to specific diseases [12, 32] (**Figure 2**). Traditional breeding relies heavily on phenotypic evaluation, which involves observing physical traits under natural or controlled conditions, making it a time-tested yet resource-intensive method.

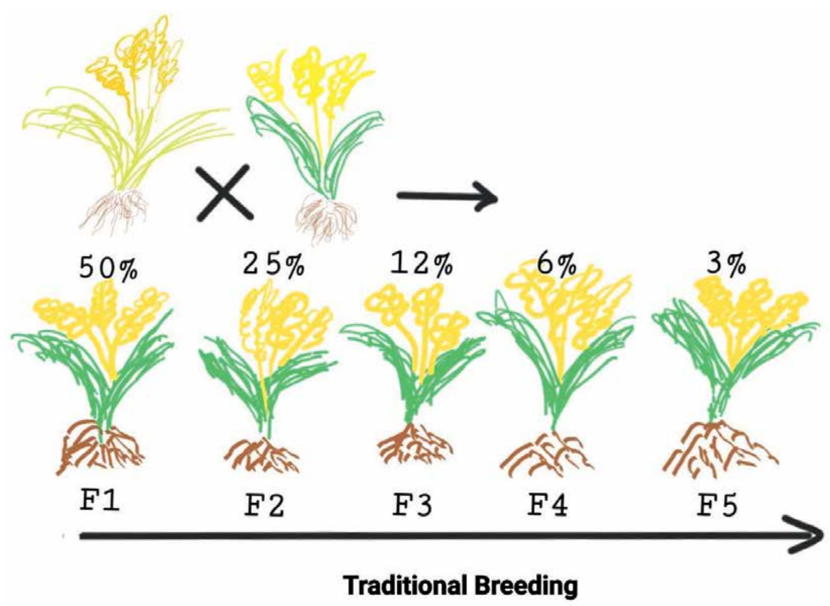


**Figure 2.**
*Traditional breeding: Scientists move desirable plant pollen to flowers carrying desired traits during the plant pollination process. Over time, they can identify new plant combinations through a process of selection. Desirable characteristics: The desired features eventually emerge in a novel plant variety during selection.*

#### *4.1.1 Key steps in traditional breeding*

##### *4.1.1.1 Germplasm selection and screening*

The breeding process begins with the identification of resistant traits in diverse wheat germplasm, including landraces, wild relatives, and existing cultivars. Screening is conducted in disease-prone environments or controlled settings to pinpoint genetic sources of resistance.

##### *4.1.1.2 Hybridization*

Resistant donor varieties are crossed with high-yielding but susceptible recipient varieties to combine resistance with favorable agronomic traits, such as grain quality, and yield potential [33].

##### *4.1.1.3 Backcrossing*

To preserve the desirable characteristics of the recipient parent while introducing resistance traits, backcrossing is employed [14, 34]. Offspring from each generation are repeatedly crossed with the recipient parent, with careful selection for resistance at each stage.

##### *4.1.1.4 Phenotypical selection*

Progeny is evaluated under field conditions exposed to pathogens or in controlled trials. Selection focuses on identifying plants that exhibit strong resistance alongside desirable agronomic performance. Multi-location trials further ensure the stability of resistance across varied environments [5].

#### *4.1.2 Advantages of traditional breeding*

- *Leverages natural diversity:* Traditional methods capitalize on the inherent genetic diversity within wheat and its wild relatives.

- *Cost-effectiveness:* These methods are generally less expensive compared to modern molecular techniques, making them accessible for low-resource agricultural systems [35].

- *Sustainability:* Breeding programs rooted in traditional techniques are environmentally friendly as they reduce reliance on chemical controls.

#### *4.1.3 Challenges in traditional breeding*

Despite its effectiveness, traditional breeding faces several challenges:

- *Time-intensive process:* Developing resistant varieties often requires 10–15 years due to the multi-generational nature of selection and evaluation.

- *Environmental dependency:* The expression of resistance traits can be influenced by environmental conditions, which may complicate the selection process.

- *Pathogen evolution:* Rapid adaptation and evolution of pathogens, particularly in response to monogenic resistance, can lead to breakdowns of resistance [34].
- *Limited precision:* Phenotypic selection may not always accurately reflect the underlying genetic basis of resistance.

### 4.2 Advanced breeding techniques for durable resistance

Modern breeding techniques complement molecular tools to create wheat varieties resilient to diseases and environmental stresses.

#### *4.2.1 Pyramiding resistance genes*

Combining multiple resistance genes (R genes) into a single genotype enhances durability and prevents rapid pathogen adaptation. This approach is particularly effective for combating fungal diseases like rusts and Fusarium head blight.

#### *4.2.2 Pre-breeding with wild relatives*

Wild relatives of wheat (*Triticum monococcum* and *Triticum dicoccoides*) harbor untapped genetic diversity. Pre-breeding programs introduce these novel resistance genes into cultivated varieties, ensuring a broader genetic base for disease resistance.

#### *4.2.3 Multi-environment testing*

Phenotypic evaluation across diverse environments ensures the stability of resistance traits under varying climatic conditions and pathogen pressures, aiding in the selection of robust cultivars.

### 4.3 Marker-assisted selection (MAS)

MAS employs molecular markers like SNPs, SSRs, and DArTs to select resistance traits. These markers are useful because they are heritable, accurate, and unaffected by environmental conditions [20, 36]. MAS techniques, including backcrossing and pyramiding of resistance genes, have been successfully applied in developing wheat varieties with enhanced disease resistance [37].

#### *4.3.1 Commonly used molecular markers include*

*Simple Sequence Repeats (SSRs):* Also known as microsatellites.

*Single Nucleotide Polymorphisms (SNPs):* The most common type of genetic variation.

*Amplified Fragment Length Polymorphisms (AFLPs) and Restriction Fragment Length Polymorphisms (RFLPs).*

#### *4.3.2 Selection process*

- MAS relies on detecting the presence of markers linked to the desired traits in a plant's genome.
- Once identified, these markers enable breeders to select offspring with the desired genetic makeup before the traits are fully expressed.

### 4.4 Genomic selection (GS) and CRISPR technology

- GS is a powerful approach that complements marker-assisted selection (MAS), focusing on estimating breeding values for complex traits using genomic data rather than requiring specific knowledge of individual genetic loci [14].

- Advances in genotyping tools, such as high-throughput sequencing, have enabled precise identification of quantitative trait loci (QTLs), aiding GS to accelerate breeding cycles and improve prediction accuracy for various traits, including yield and stress resilience.

- GS integrates large-scale genotypic and phenotypic data, incorporating advanced statistical models such as genomic best linear unbiased prediction (G-BLUP) and Bayesian methods for trait prediction ISPR Technology.

- CRISPR-Cas systems have revolutionized precision breeding, enabling targeted gene editing to enhance traits such as disease resistance, stress tolerance, and productivity [38].

- Recent advancements include base editing and prime editing tools for more refined and precise modifications.

Examples include editing genes responsible for improving disease resistance or modifying key traits in economically significant crops like wheat and rice (25† source) on CRISPR with genomic selection strategies (**Figure 3**) further accelerates crop improvement by combining targeted genome editing with robust predictive modeling [39].

### 4.5 Genetic modification and gene editing for disease resistance

Genetic modification (GM) and gene editing are powerful biotechnological resources that can help to improve the disease resistance of diverse organisms. Thanks to molecular biology advancements, such as the ability to locate certain genes that respond to diseases, one can enhance the body and shield it from pathogens [34].

Some of the major areas include one of the greatest uses has been in the production of pest- and disease-resistant crops in agriculture. For example, genes from pest-resistant sources can be transferred to economically important crops to eliminate the need for using poisonous chemicals and also increase food production. Similarly, CRISPR-Cas9 (**Figure 3**) an exact gene editing technology has been used to knock out susceptibility genes in plants that provide customized protection against eye-striking pathogens like fungal rusts and bacterial blights [40]. That is why, in the field of medicine, it is easy to discern the potential of genetic editing in the framework of measures designed to prevent genetic diseases and infections. In people, therefore, gene editing has the potential to cure or at least erase diseases like sickle cell anemia and cystic fibrosis by correcting defective genes. In addition, scientists are studying gene editing techniques to introduce virus immunity into cells with the help of CRISPR to destroy HIV genomes in humans. Another example is the development of disease-resisting animals [14].

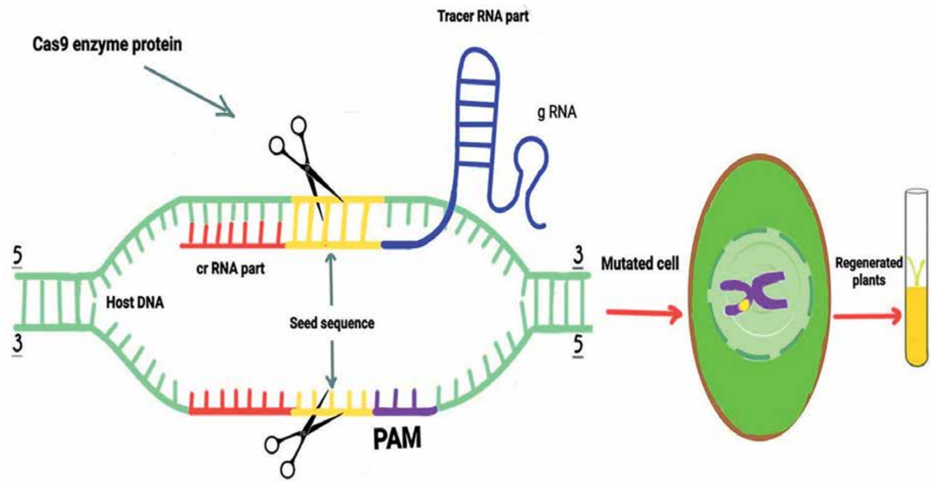


**Figure 3.**
*A single Cas9 enzyme functions in a monomeric protein complex that forms alliances with guide RNA (gRNA). crRNA and trans-activating CRISPR RNA (tracer RNA) make up the guide RNA (gRNA), which has crRNA functionality to recognize 20–22 bp host DNA. A single 2–6 bp sequence named the protospacer adjacent motif (PAM) serves as an essential requirement for the Cas9 nuclease to activate its function. The PAM site exists 3–4 nucleotides behind where the cut will occur. A PAM motif exists 5 nucleotides above the seed sequence. The binding of gRNA to target DNA together with Cas9 DNA cutting depends on correct matching between seed sequences and PAM sites. The CRISPR/Cas9 system produces single-stranded nicks together with double-strand breaks. The components deliverable to cells eradicate the need for cloning the built construct. The target recognition performance of this system proves strong, with minimal vulnerabilities and low toxicity levels. The system can be easily combined with other methods and delivers maximum value for its cost.*

## 4.6 RNA interference (RNAi) and its role in pathogen control

RNA interference (RNAi) refers to a naturally occurring mechanism and cellular pathway that is involved in gene silencing and defense of an organism against pathogens. Originally identified in plants and subsequently finding its utility in animals and fungi, RNAi runs via small RNA molecules consisting of small interfering RNAs (siRNAs) and microRNAs (miRNAs) that target messenger RNA (mRNA) by pairing and leading to the mRNA's degradation or repression of translation [6].

Discussing RNAi applicable to pathogen control, two main areas were identified: agriculture and medicine. Of course, plants employ RNAi to defend against viruses since. This mechanism has been used by scientists in genetically modified crops that can produce siRNAs that give resistance to destructive pathogens; the pathogens include viruses, fungi, and insect pests. For instance, RNA interference reduces vulnerability to insects; pests cotton bollworm and maize rootworm are combated through RNA interference in protecting crops such as cotton and maize from chemical pesticides [28].

In human medicine, RNAi opens several potential lines of treatment against infectious diseases. RNAi-based therapeutics are being developed to treat viral diseases like HIV, hepatitis B, SARS-COV-2, and others. In so doing, these treatments offer an exact and reversible means of controlling disease by preventing viral genes or host factors important for viral replication.

Thus, the high focus and the ability to target practically any gene make RNAi an indispensable instrument for studying pathogen biology. Biologists use RNAi to generate dysfunctional pathogens to understand the role and flaws of a particular gene in assisting in the creation of drugs or a vaccine.

However, issues like delivery efficiency and target specificity remain obvious issues holding back RNAi technology. These concerns are being tackled through improvements in nanoparticle delivery and tissue-directed techniques, opening the possibilities for the use of RNAi in pathogen control.

### 4.7 Sustainable disease management strategies

Integrated Disease Management (IDM) remains the cornerstone of sustainable agriculture, offering a comprehensive approach to minimize losses and environmental impact. While IDM is a holistic disease management approach different from other singular control measures, it incorporates cultural, biological, chemical, and mechanical tools and seeks to reduce economic losses together with environmental and health hazards. This approach targets the disease cycle, parasite-host-environment interactions, and the host's response to provide effective control measures that are ecosystem-specific [41].

The persistent use of resistant crop varieties remains an effective intervention on the basis of which IDM has been founded upon. For example, resistant rice varieties like IR64 are important in controlling the rice blast by *Magnaporthe oryzae* [42]. This fungal disease is also prevented by water management, adequate spacing during planting to reduce humidity, and by using organic enemies like *Trichoderma* spp. in combination with fungicides [43].

Likewise, IDM strategies have been found quite useful in controlling late blight in potatoes, a disease resulting from infection by *Phytophthora infestans*. Like Sarpo Mira-resistant cultivars, rotation farming to ensure that pathogen accumulations do not affect the plants and weather-based forecasting are key measures. Further, beneficial microbes, including *Pseudomonas fluorescens*, play a dual role of inhibiting the pathogen; fungicides are applied only during outbreaks following Fry and Goodwin [44].

As applied to wheat rust disease caused by *Puccinia* spp., IDM encompasses growing resistant varieties such as those containing the Sr31 gene, crop rotation to avoid subjecting an area to one disease at a time, and the use of biocontrol agents such as *Bacillus subtilis* to build up the plant's immune system. Chemical fungicides, on the other hand, act as a standby, used at sensitive stages of disease progress [45].

Like other crops, IDM also plays an important role in tomato crops, especially against Fusarium wilt, which is caused by *Fusarium oxysporum* f. sp. *lycopersici*. BHN-1025 developed as a resistant hybrid, solarization to sterilize soil infected by the pathogen, and inoculation with *Trichoderma harzianum* take up the practice of disease management. Further, biofungicides and minimal chemical treatments such as methyl bromide are utilized for particular control [7].

## 5. Environmental and agronomic factors influencing resistance

### 5.1 Impact of environmental stress on disease resistance

Stress in this context is defined as any pressure that exerts influence on the organisms they affect, thereby reducing their capacity to fight diseases, as well as, in most cases, compromising their immune systems, making them more susceptible to infections. Factors such as water stress, heat shock, high salinity, or pollution interfere with physiological and biochemical processes that are well-needed to support a resilient immune response [46].

There is evidence that the immune system is often exacerbated by environmental stress in areas where the disease resistance is threatened [11]. For instance, drought stress reduces the mobility of ROS in wheat, which is central in signaling pathogen attacks. In animals, heat stress decimates immune cell production in dairy cattle, therefore making it easy for them to be infected with diseases such as mastitis and respiratory infections. Likewise, in the growing of shrimp, the toxins such as ammonia and heavy metals reduce the overall health-combating ability of those natural defense system of the crustaceans, which results in bacterial diseases like vibriosis [47].

Stress conditions also reduce the strength of defenses that are put in place to ward off infectious agents. Consequently, high salinity of tomato tissue can lead to tissue decay that creates a point of entry for some fungi, such as the Fusarium oxysporum [41]. Damaged epithelial layers in fish exposed to pollutants in aquatic environments have a higher susceptibility to parasitic diseases, including those caused by *Ichthyophthirius multifiliis*.

Stress also aggravates hormonal imbalances and affects immunity in a reverse manner. For example, in grapes, ABA accumulation because of drought stress inhibits SA-dependent defenses, making resistance to powdery mildew. In poultry, high temperature increases the level of corticosterone, which decreases the capacity of birds to combat diseases such as coccidiosis, a parasitic disease that affects growth and production [12].

Further, stress makes organisms give up defense and focus on how to survive. Under drought stress, rice plants have low investment in defense proteins, including pathogenesis-related (PR) proteins, thus making them more susceptible to sheath blight disease caused by *Rhizoctonia solani*. Likewise, in bees, exertion resulting from exposure to pesticides or loss of habitat leads to a drain of energy away from colony defense against diseases such as Nosema and Varroa destructor mites [48].

The measures taken in order to combat half of the solution involve developing stress-resistant crops and animals. For example, there are drought-tolerant maize qualities that retain ROS production when water is scarce, improving pathogen combat. In cattle, agents like vitamin E and selenium, which are nutritive supplements, work to enhance immune response during heat stress promotion. Further, mechanized practices like mini and subsurface irrigation, integrated nutrient management, and soil salinity slowly affect stress on plants, thereby decreasing disease threats [5].

This makes it obvious that using a comprehensive approach that includes stress reduction measures alongside improved disease control measures will be important. Such efforts are crucial for the purpose of developing sustainable productivity of natural and agronomic systems in the climate change circumstances.

### 5.2 Role of crop rotation, tillage, and other management practices

Crop rotation, tillage, and integrated management practices are several important measures for sustainable agriculture, as they support soil conservation, enhance yield, and reduce pests and diseases. These practices ensure an optimal agroecosystem by controlling pathogen accumulation, improving nutrient recycling, and improving the population of friendly soil insects.

#### *5.2.1 Crop rotation*

Crop rotation is perhaps one of the earliest and most successful techniques of soil management and disease control. In this way, by growing different crops in a sequence, a cycling of definite pests and pathogens that are crop-specific is prevented. For instance, they mentioned that cereal crops are rotated with legumes like soy, hence improving the nitrogen status of the soil as well as decreasing incidences of diseases, for instance, root rots and Fusarium wilt. Non-host crops also reduce nematode prevalence, such as the root-knot nematodes, which prefer monoculture crops to the exclusion of other crops in a rotation cycle [41].

#### *5.2.2 Tillage practices*

Intensive and selective tillage, therefore, impacts disease management and soil structure when appropriately applied. Conservation agriculture, such as minimum tillage or nil tillage farming, or no-till farming, retains the organic matter in the soil and stimulates soil microbial activity that, due to competition with the pathogenic ones, suppresses their activity. But, deep and frequent tilling has negative effects on biological factors of the soil, resulting in enhanced erosion mainly due to harsh weather and nutrient loss and enhanced diffusion of soil-borne diseases. Conservation tillage, where crop residues remain on the field, is most useful in weed suppression and encouraging tiny predatory insects [49].

#### *5.2.3 Other management practices*

1. *Cover cropping*: Winter crops like clovers, rye, and vetch improve soil structure, minimize erosion, and conserve fertilizers by covering the ground during the off-season. They can also lock up pathogens on the soil surface and prevent them from infecting the next planted crops.

2. *Integrated pest management (IPM):* Focus on biological, chemical, and cultural methods makes Integrated Pest Management different from traditional chemical use and hence reduces pesticide dependency. For example, the use of such friendly pesticides as ladybugs to control aphids or the use of pheromone traps to monitor bug populations is environmentally friendly [50, 51].

3. *Soil amendments*: Compost, manure, or biochar enhance the fertility of the soil and also increase microbial richness. These amendments improve a plant's ability to withstand diseases by fending off a weak or damaged rhizosphere.

4. *Irrigation management:* Good timing and practices like drip irrigation reduce water stress and conditions that encourage fungal diseases such as the powdery mildew.

5. *Sanitation and field hygiene:* Gerbils must avoid keeping crop residues on the farm since they host overwintering bugs and diseases. Controlling cleaning of equipment and rotational fields helps to minimize the spread of disease.

## 6. Pathogen evolution and resistance breakdown

### 6.1 How pathogens evolve to overcome resistance

The ability of pathogen agents to evolve and adapt gives disease management a major problem with its sustainability. As expected, pathogens share a high recombination rate, which allows them to evade host immunity through different evolutionary processes. These include gene mutations, horizontal gene transfer, and recombination that make input to the development of resistance-breaking strains. But, it is specifically the relentlessly strong selective pressures created by large-scale use of single-gene resistance in crops that has been a leading cause of resistance breakdown [52]. However, such resistance genes prove to be effective only at the beginning, experiencing strong directional selective pressure, where the subsequent pathogens are allowed to evolve means to overcome the resistance process. This, in the long run, weakens the resistance and brings back diseases, which are hugely troublesome. Further, pathogens may undergo epigenetic changes by altering gene expression, the pathogens' effectors may produce multiple similar proteins and metabolic rates may be tuned up or down to avoid host immune response. The parasite-host co-evolution supports the evolved complexity of patents and genes in the pathogen, with relation to the selective advantage of the host defense genes. To design sustainable ways of addressing resistance breakdown, it is important to know the molecular and evolutionary processes behind it. This involves the use of quantitative resistance, the stacking of different resistance genes, and the adoption of cultural practices that will lower the intensity of participants to pathogen populations [44]. Integrating genomic tools and other prediction models into pathogen surveillance represents tractable strategies with regard to identifying pathways of evolution and preventing the breakdown of resistance.

### 6.2 Examples of resistance breakdown in wheat cultivars

Evolution of pathogen strains is one of the most significant concerns in world agriculture, especially in the area of wheat production. At times, pathogens become capable of incubating genetic resistance developed in the wheat cultivars, and this has an inherent disadvantage of resistance breakdown and disease susceptibility. This is mainly due to the genetic variation and high rates of mutation in the pathogen's gene pool and increased production of high-resistance wheat varieties with similar genes [22].

A striking example of the breakdown of this kind of resistance has been recorded in wheat-rust diseases, specifically *Puccinia graminis* f.sp. tritici causing stem rust. The use of the Sr31 resistance gene in widely grown wheat cultivars enabled to protect them against rusts for decades. However, the discovery of the highly aggressive Ug99 lineage of East Africa in the late 1990s reduced the efficacy of Sr31, leading to severe epidemics and yield losses [53]. This drew emphasis on the need to introduce more resistance genes and use approaches like pyramiding, whereby a number of resistance genes are combined in order to extend the time the pathogen takes to evolve resistance to the gene.

Likewise, the studies have been conducted on the degradation of resistance against Zymoseptoria tritici, the pathogen associated with septoria tritici blotch (STB), in various wheat varieties. Although resistance genes such as Stb6 gave initial control, these failed due to the fact that the pathogen is capable of adapting and, hence, overcoming the launch of single-gene resistance. This explains why a combination of strategies and approaches, such as using quantitative resistance and enhanced and sustainable agronomic practices, is necessary to avert STB effects [54].

The life cycle and evolutionary trends of the pathogens call for constant surveillance, propagation, and adoption of integrated pest management approaches.

Understanding the wheat genes and its proteins through molecular and genomic tools is very useful for locating new resistance genes and estimating prospective breakdowns of resistance, thus sustaining wheat production from the stranglehold of new threats [39].

### 6.3 Strategies to mitigate pathogen adaptation

Crop protection is a complex process that reflects the struggle that is an unceasing biological evolutionary process between plants and pathogens. As such, the generic concept of pathogens, which are fungi, bacteria, or viruses, for instance, has an inherent flexibility that allows them to outcompete inherent host defense mechanisms. These coincide with the breaking down of resistance whereby the former protection mechanism is no longer sufficient to release the host from the strain of the new pathogen genotypes [41]. This is a result of the positive Darwinian selection by host resistance genes, which act proactively to disallow the pathogen to infect the plant, yet this pressure creates an avenue for the development of other variants of the pathogen, thus overcoming the host immune system.

Population heterogeneity is perhaps the most significant factor influencing resistance breakdown among the pathogens. Viruses, in particular, and especially those with high mutation rates, can relatively quickly produce new, dangerous types of pathogen. Such variants may possess mutations that help them colonize crops that have developed resistance genes against them. Moreover, the concentration, especially in breeding programs, of single-resistance genes to improve crop resistance to pathogens shortens this cycle as pathogens are subjected to constant selective pressure. For resistance not to be easily overridden by pathogens, several approaches are needed [9]. One of the promising approaches in the practical implementation of this approach is the integral incorporation of several resistance genes into a given crop. This approach ensures that methods of resistance that develop in the pathogen do not consistently overpower all of the mentioned forms of resistance at once. This approach postpones the breakdown of resistance and also provides lasting control of pathogens for shorter and longer terms if needed. The other mechanism involves diversification and crop rotation. This may be done by growing crops with varying resistance factors or different crop varieties in the same field or by growing different crops from different genetic strains so the amount of pressure put on any one pathogen is less. This practice can help disrupt the life cycles of pathogens and minimize the probability that a pathogen which happens to have developed resistance to a particular mechanism. Integrated Pest Management (IPM) is also another important factor when addressing long-term pathogen persistence [27]. Thus, IPM has an extensive approach of using both biocontrol and chemical control, as well as cultural control, in order to heavily reduce the instances of resistance issues. This study shows that through the adoption of agricultural, and cultural practices, including the use of resistant cultivars, proper irrigation and integrated soil health, and management with biological control agents and thoughtful chemical application, the principles of IPM can provide an environmentally friendly and more sustainable approach toward the control of pathogens. Last but not least, conePCR and recently evolved CRISPR/Cas9 have prospective angles for countering pathogen adaptation. These technologies make it possible to exert fine control on plant genomes, which can then be used to create new resistance types or to increase existing ones. These techniques help breeders develop crops resistant to a wide range of pathogens without the likelihood of high-velocity breakdown of resistance [14, 36].

## 7. Emerging threats and future prospects

### 7.1 Emerging wheat diseases due to climate change

Global warming has emerged as one of the leading causes of new wheat diseases that are a threat to production and food security. Increased temperatures, changes in precipitation regimes, and more frequent and severe storms and floods have created favorable conditions for pathogens that infect wheat crops. Climatic diseases that used to occur in certain geographical locations are today migrating to other parts, with disastrous effects [55].

For instance, *Puccinia graminis* (stem rust) and Zymoseptoria tritici (septoria leaf blotch) diseases are appearing more frequently in areas where they were previously tamed. Milder weather conditions result in the survival of germs over winter periods, while humidity differences result in the rapid dissemination of fungal spores. For instance, new pathogen races that cause increased virulence were observed in stem rust where Ug99 was identified, therefore incurring the need for developing competently durable wheat varieties and efficient management practices [22].

Moreover, climate change affects one or the other by creating opportunities for the development of new diseases within the host-pathogen model. Fusarium species causing Fusarium head blight (FHB) have recently increased in temperate regions and are aggravated by increased growth seasons with humidity. These resultant plant pathogens are not only known to lower yields for the grain but also affect the quality and safety of wheat products as a result of the mycotoxins they produce [5].

To overcome these challenges, therefore, future research should aim at developing durable resistant wheat varieties as well as disease early warning systems using information and communication technology tools such as artificial intelligence and remote sensing. Like most crop protection measures employed in IPM, crop rotation and the selective use of fungicides also depend on climate change.

### 7.2 New technologies for disease monitoring and forecasting

Plant diseases present one of the most complex problems in the world today in terms of the availability of food due to its dynamic nature occasioned by climatic changes, the emergence of new diseases, and international trade. Technology has, however, evolved in neighboring fields to change how these threats are detected, forecasted, and mitigated. Given improvements in the use of remote sensing and machine learning, researchers are now capable of detecting diseases and providing responses depending on the breakout incidents in record times [56].

#### *7.2.1 Remote sensing technologies*

Eradicating diseases can be made easier by using satellite imagery and aerial sensors from drones because they help map out large areas on the health status of crops in real time. Both multispectral and hyperspectral imaging are able to diagnose variations in plant functions invisible to the human eye, for example, chlorophyll fluorescence or thermal stress, which could precede the formation of disease symptoms. It facilitates early intervention, thus minimizing diseases' effects on yield [56].

#### *7.2.2 Machine learning and artificial intelligence*

These breakthroughs are changing the disease forecast models, especially through the use of big data analytics and machine learning algorithms. Most of them involve disease data from previous years, climate data, and data on the health of the soil, and they are able to give a highly accurate prediction of disease outbreaks [39]. Bases like these enable farmers, together with policymakers, to make effective decisions in relation to resources to be used, plus a reduction in losses encountered in crop farming.

#### *7.2.3 Genomic surveillance and pathogen tracking*

Recent developments in other areas of genomics, including biosensors based on CRISPR and short portable sequencing, allow for the quick identification of strains and mutations of pathogens. These tools not only enhance knowledge on pathogen evolution but also enable early generation of resistant crop varieties and optimum biocontrol measures [13].

### 7.3 Future research directions and breeding strategies

With the ever-increasing global population and the ever-increasing demand for food, Triticum species are under increasing pressure. Increased challenges like climate change, new virile diseases infecting wheat, and reduced genetic stock for wheat varieties call for new ways of production [39]. Therefore, there is a need for future research to undertake the challenges by applying developments in genomics and modern biotechnology, as well as precision agriculture.

This has made the improvement of climate-resilient wheat cultivars that can perform well under abiotic stresses, including drought, heat, and salinity stresses, a focal area of improvement. The inclusion of technologies such as CRISPR-Cas9 in breeding systems provides unique chances to advance defined characteristics quickly. Additionally, attempts must be made to harness the wild gene pool in wild relatives of wheat, which actually harbors genes for resistance to disease and other environmental stresses [14].

In like manner, breeding strategies have to address other problems to feed the people in the world today; one of these is disease and malnutrition because the nutritional value of wheat has to be enhanced. Other strategies for reducing micronutrient malnutrition include biofortification of crops for zinc and iron will go a long way in solving the hidden hunger problem in vulnerable groups.

Last but not least, the establishment of cross-sectorial networks of geneticists, agronomists, and data scientists can help lead this adoption of predictive breeding models. Such bred models based on artificial intelligence and big data shall assist the breeders in selecting the right genotypes more efficiently and more accurately. The global wheat industry should respond to these emerging threats by shifting focus on strategic research and innovative breeding strategies to help the industry grow in its fight for food security for the future generation.

## 8. Case studies

### 8.1 Case study of rust resistance in wheat (*Puccinia* spp.)

Diseases being a real threat to the growth of the wheat produce are the rust diseases, including stem rust that is in the order Puccinia graminis f. sp. tritici, leaf rust that is in the order P. *triticina*, and stripe rust that is in the order P. *striiformis* f. sp. *tritic*i. These diseases can drastically cut crop yields, and this is a big danger to food security in the world today. In recent years, breeding activities have concentrated on improving rust-resistant wheat through genetics and a combination of major Resistance (R) genes and Adult Plant Resistance (APR) genes.

## 8.2 Genetic approaches to rust resistance

Resistance (R) genes: R genes give race-specific resistance through pathogen recognition of effector molecules [6]. They provide very strong barriers and frequently are transient in nature simply because of what this pathogen does to overcome these barriers. For example, the Sr31 gene, which was very effective for several years, has been rendered less effective by the appearance of the Ug99 vigorous race. In reality, though, they are extremely sensitive to pathogen pressures, but they are useful for the first line of defense, especially when the R genes are in gene stacks to mitigate the pathogen angle side of things [22].

Adult Plant Resistance (APR) genes: These genes, which function at or post-mature plant stage, offer a measure of resistance. The genes, for example, Sr2 and Lr34, delay pathogen reproduction and lessen lesion size but do not eradicate the pathogen. As compared to R genes, APR genes have less strong effects, but under field conditions, APR genes are more effective. For instance, Sr2 has already been mentioned as one of the main reasons for using this gene in global breeding programs, although it cannot provide reasonable protection on its own under high disease pressure [57].

### *8.2.1 Challenges in breeding rust-resistant wheat*

Like any other source of resistance, breeding for rust resistance needs to combine sources of R and APR genes for both short-term and long-term resistance. R genes are thought to command immediate and successful defense mechanisms against a pathogen, but the genetics of pathogens mutate and result in an outbreak of the particular disease. Some APR genes are durable but need to be pyramided with other genetic resources to give a reasonable level of resistance [36].

Past victories show how it is possible to integrate these styles. For instance, the wheat variety "Hope" that came into the market in the 1920s possessed both Sr2 as well as other resistance genes to overcome stem rust during the interleukin epidemics in the early twentieth century. In the same way, CIMMYT (International Maize and Wheat Improvement Center) has used the APR genes, such as Sr2 and Lr34, to develop the wheat lines nearly resistant to rust diseases [19].

### *8.2.2 Molecular insights and future directions*

New knowledge of rust resistance has emerged due to the progress in molecular biology. The cloning of other APR genes, Lr34 and Yr36, has helped understand their function and shown that they encode proteins like ABC transporters and protein kinases. These insights directly enable precision breeding to harnessfully stack R and APR genes toward enhancing resistance durability [58].

The deployment of molecular technologies such as DNA and, molecular breeding, and gene editing tools provides an exciting prospect of transcending the drawbacks of conventional breeding. For instance, a concept known as resistance gene cassettes, where many resistance genes are condensed into one area and then put into wheat genomes to hasten generations and enhance stable resistance across various settings, is being researched [11].

## 8.3 Case study of Fusarium head blight (FHB) resistance

Fusarium Head Blight, commonly known as a head scab disease, which is mostly produced by Fusarium graminearum, is a dangerous and effective disease of wheat and other cereal species [59]. In addition to lowering grain yield, this disease infests the harvested grain with such toxins as deoxynivalenol (DON), which is dangerous to human and animal consumption. Selecting for FHB resistance has now emerged as a top priority of cereal breeding programs across the globe [60].

### *8.3.1 Types of FHB resistance*

*FHB resistance is categorized into several types based on specific traits:*
Type I resistance: Susceptibility of the initial infection site as a barrier to decrease the ability of the fungus to penetrate the plant tissue.
*Type II resistance:* Stabilitycntrolling resistance to the spread of the fungus within the spike, which has been described to provide the highest level of FHB resistance.
*Type III resistance:* One is the capability to limit the accumulation of this mycotoxin that lowers the concentration of DON in the grain.

#### *8.3.1.1 Breeding strategies*

FHB resistance is categorized into several types based on specific traits:
Type I resistance: Susceptibility of the initial infection site as a barrier to decrease the ability of the fungus to penetrate the plant tissue.
Type II resistance: Stability and expression of major genes controlling resistance to the spread of the fungus within the spike, which has been described to provide the highest level of FHB resistance.
Type III resistance: One is the capability to limit the accumulation of this mycotoxin that lowers the concentration of DON in the grain.

#### *8.3.1.2 Challenges in FHB resistance breeding*

- *Environmental influence*: This is because FHB severity is influenced by generous environmental factors, and it is hard, often compared to achieving the similarity in resistance.

- *Complexity of resistance:* Resistance is most frequently a quantitative and polygenic response that needs rigorous breeding and evaluation for efficacy in different environments.

- *Balancing traits:* The development of FHB resistance should not be at the cost of yield, grain quality, or other desirable quality attributes.

- *Future directions:* But for the crop, resistance to FHB has remained a chimera until recent developments in genomics offered new avenues. Genomic tools such as the GWAS and genomic selection are being used to discover new resistance genes as well as to improve the accuracy of predicting resistant phenotypes. Furthermore, they admit genetic editing options that include CRISPR-Cas9 tools, which may be useful to manipulate the genes that make a plant susceptible to pests or amplify protective loci [26].

## 9. Policy implications of wheat disease management

As a major source of global food security and income, wheat disease control needs strong policies that meet these essential needs. The combined harm from wheat diseases to the economy, society, and environment shows the need for urgent policy action. Our wheat policies need to create systems that prevent threats while controlling diseases through innovation and equal access to resources for sustainable results (**Figure 4**).

### 9.1 Strengthening food security policies

Wheat forms the foundation of millions of diets worldwide, but its yearly harvest can suffer from plant diseases that threaten global food availability. These diseases reduce crop yields, which increase food shortages most strongly in impoverished areas.


**Figure 4.**
*Policy implications of wheat disease management.*

#### *9.1.1 Recommendations*

- *Invest in disease-resistant varieties:* Public funds should go to wheat breeding projects for creating and spreading disease-resistant wheat types that produce well.
- *Subsidized access to resistant seeds:* Make crucial new plant varieties affordable for smallholder farmers living in poor countries.
- *Global food reserves:* Keep emergency wheat stores ready to deal with plant diseases that harm farms.

### 9.2 Encouraging Research and Development (R&D)

Good disease management depends on constant new ideas and solutions (**Figure 4**). Rules need to reward scientists developing new molecular tools as well as techniques to breed plants and defend crops from emerging diseases.

#### *9.2.1 Recommendations*

- *Public-private partnerships*: Help different research groups work together with private businesses and international groups to share resources for research projects.
- *Increased R&D funding:* Allocate substantial government budgets to research in genomics, gene editing (e.g., CRISPR), and Integrated Disease Management (IDM).
- *Open data platforms:* Help set up worldwide databases to watch pathogens and their genes so teams can take action quickly.

### 9.3 Climate change adaptation and sustainability

Wheat health problems grow worse because of climate change, which affects how diseases impact plants and fungi. Policies must encourage farmers to adopt farming methods that help the climate today and in the future.

#### *9.3.1 Recommendations*

- *Climate-resilient varieties:* supports wheat breeding research to create new varieties that fight diseases while enduring varied weather patterns.
- *Forecasting and early warning systems:* Put money into weather-based disease forecasting tools to help us predict breakouts and plan prevention steps ahead of time.
- *Environmentally friendly practices:* Support IDM strategies by reducing chemical applications while allowing workers to use natural pest fighters and farming techniques.

### 9.4 Supporting smallholder farmers and equity in disease management

Smallholder wheat farmers make up most of global production yet struggle to fight diseases because they lack modern tools and good information (**Figure 4**).

#### *9.4.1 Recommendations*

- *Capacity building:* Public education centers should teach farmers how to spot plant diseases and take action.
- *Subsidies and financial support:* Offer monetary support for people who use disease-resistant farming materials and implement IDM strategies.
- *Technology transfer:* Help farmers in developing nations receive the latest molecular testing tools and diagnostics through easy access.

### 9.5 International collaboration and regulatory alignment

Countries worldwide must unite to fight wheat diseases effectively (**Figure 4**). The government must develop rules that fit all countries and help teams work together across borders.

#### *9.5.1 Recommendations*

- *Pathogen surveillance networks:* Wheat disease experts need to connect worldwide to track and share new wheat threats.
- *Harmonized regulatory frameworks:* Strengthen biosafety rules worldwide to help speed up the process of getting genetically modified and gene-edited wheat to market.
- *Capacity building in developing nations:* Support developing nations with technology and money to build their agricultural disease control systems.

### 9.6 Addressing economic and trade implications

Agricultural disease outbreaks affect international trade markets, causing market prices to change unpredictably and hurting world financial systems. Policies need to control wheat disease's impact on markets and protect both traders and market participants (**Figure 4**).

#### *9.6.1 Recommendations*

- *Stabilizing wheat markets:* Create trading rules to protect products from going missing when diseases strike.
- *Disease-free certification:* The government needs to enforce strong plant health rules that stop dangerous wheat diseases from moving between countries.

### 9.7 Ethical and social considerations

Our society and ethics need attention when scientists use complex tools such as CRISPR and transgenic methods. Decision-makers need to tackle scientific development risks while gaining community acceptance of new technologies (**Figure 4**).

#### *9.7.1 Recommendations*

- *Public awareness campaigns:* Share important information about how modern breeding practices protect people and help agriculture.
- *Ethical oversight committees:* Set up separate groups to assess potential ethical troubles from wheat genetics changes.
- *Regulatory transparency*: Make all decision-making about new technologies open and include everyone whose work will be affected by these decisions.

## 10. Conclusion

This chapter discussed various complex bilateral interactions among gene sets, gene expression, and the resistant phenotype in Triticum [61]. In our previous sections, we discussed the various ways through which plants defend themselves against diseases, embracing physical and chemical barriers. The debate on breeding for disease resistance underlined the use of traditional and advanced tools in the development of high-resistance wheat cultivars [34]. However, the chapter also talked about threats and the future discussion of them, stating how threat novelty and constant changes in climate and pathogens require adaptations [5]. The evolution of the pathogens and breakdown of resistance highlighted the fact that there is an urgency in regard to the co-evolution cycle between wheat and its pathogen enemies.

Other factors, such as environmental and agronomic factors, were also examined in order to show how external conditions affect resistance genes and allele expression or their stability [9, 62]. Lastly, we explored the molecular-level strategies for increasing resistance and explored how genetic engineering, CRISPR, and omics technology are the future of wheat protection against diseases. Looking to the future, QTL-based approaches with active support of modern technologies accompanied by an understanding of ecological and agronomic factors are necessary for maintaining and improving disease resistance in Triticum [12, 53]. The improvement of wheat resilience against future threats requires researchers to work together with breeders and policymakers to establish adaptable systems that enhance wheat security combined with sustainable environmental solutions [55].

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Section 2

# Climate Resilience and Environmental Adaptation

Chapter 4

# Wheat Phenology and Yield in a Mediterranean Scenario of Climate Change

*Maria Conceição Gomes, Rita Costa, Sara Rodrigo, Víctor Rolo, Nuno Pinheiro, Ana Sofia Bagulho, Armindo Costa and Benvindo Maças*

## Abstract

Wheat is a crucial crop for food and nutritional security worldwide, but it has special importance in the Mediterranean basin. Nowadays, the wheat crop is facing significant challenges due to climate change; modification in the rainfall patterns or temperature increases are boosting the probability of yield production gaps. In this study, we evaluated the effect of winter and spring rainfall, as well as minimum and maximum temperature in these two seasons and sowing date, on multiple composes of wheat yield in the Mediterranean area. Low winter rainfall (<100 mm) together with a late sowing date (later than December 31) was described as the factor decreasing to a greater extent, wheat grain yield, yielding any tested genotype less than 4200 kg $ha^{-1}$. Similarly, sowing date and its interaction with minimum winter temperature decrease TGW (Thousand Grain Weight). Protein content seemed to be more influenced by crop management than by climatic conditions; even when late sowing in cold winters or rainy winters can help to achieve higher grain protein content, close to 80% of the protein data ranged between 11 and 17%. The sowing date correlates negatively with days to heading (DTH), implying that the later the sowing date, the shorter the DTH period.

**Keywords:** phenology, soft wheat, climate change, breeding, food security

## 1. Introduction

Wheat grains are one of the major sources of calories (provides 50% of the world's caloric intake) and essential nutrients for human health: proteins, minerals (Cu, Mg, Zn, P, and Fe), vitamins (B-group), and dietary fiber [1]. An average of 130 kg per capita is consumed in the Mediterranean region, and the highest is in North African countries, where it is 200 kg per capita. Every year, 12.1 thousand to 6.6 million hectares of wheat are harvested; it is the main staple crop and key to food security in the region. Despite the efforts to develop cereal agriculture and increase production, countries in the Mediterranean basin and North Africa can no longer produce enough wheat to meet their domestic demand. Today, more than 50% of the cereals consumed in those regions are imported [2].

It is well known that the Mediterranean area is one of the regions worldwide most susceptible to episodes of drought and heat [3]. This fact is aggravated by climate change, predicting the literature [4] a warmer and drier future scenario, with a shift to less uniform rainfall distributions resulting from higher temperatures [5]. According to Todaro et al. [6] and Tarín-Carrasco et al. [7], from the mid-1980s to the beginning of the twenty-first century, annual rainfall has decreased by 10–40%, with hot spots for changes in wetter periods (spring and autumn). In addition, the projections show an increase in the global temperature from 1 to 5°C, with the highest warming rates occurring in summer [8], but with more than 1°C increase in spring [9], which can severely affect winter cereals cropping. Wheat varieties have an optimal temperature between 15 and 25°C, making them highly sensitive to climate change. The annual mean temperature in a warmer region like the Mediterranean basin had been supposed to be increased by 3–4°C, which may lead to a yield reduction of 6.0 ± 2.9% [10, 11]. In addition, water scarcity will present a major limiting factor for crop production, both with respect to lowering the total amount and also due to more irregular precipitation patterns, as well as the higher evapotranspiration resulting from higher temperatures and larger vapor pressure deficit [12]. According to Ait-El-Mokhtar et al. [13], rising temperatures will lead to 20% higher evapotranspiration by 2050 and 40% by 2080.

Climate change also plays a negative impact on plant-pathogen interactions: at the level of pathogen dynamics, the environmental shifts enable pathogens to extend their geographic range, helping in their adaptation to new agroecological zones, and making easier more virulent episodes, conferring to the pathogens the ability to overcome host resistance or even to infect new host species. On the plant side, many resistance genes are temperature sensitive and/or in view of the aggressiveness of the pathogen, they become ineffective. Thus, it is known that many wheat resistance genes are temperature sensitive, including those for Hessian fly [14], rust [15], and Fusarium head blight [16]. Climate models predict that heat and drought will favor more wheat diseases in the Mediterranean region than before [17, 18]. Another important aspect of wheat is its nutritional value. Drought and heat events differentially regulate protein and starch accumulation, and mineral metabolism in wheat grains and change grain quality. These changes affect grain weight, nutrient and anti-nutrient content, fiber, protein content and composition, starch granule structure, and free amino acid composition [19], all of which are important for human nutrition. In addition to that, different agronomical practices have been adopted to ensure sustainable wheat yields across the Mediterranean basin. Thus, literature recommends some practices to increase soil water retention, such as the enhancement of soil organic matter [20], the reduction of the tillage [21], or the management of a crop rotation with legumes, irrigation or nitrogen fertilization [22, 23]. To address all the above-mentioned constraints we need to develop climate-resilient, multi-stress tolerant and nutritionally enhanced wheat varieties. This is in line with Mediterranean and global agricultural goals. However, breeding to high-yielding wheat varieties showing adequate technological quality and resistance to biotic and abiotic stresses, is not an easy task, since these traits can be negatively correlated or not correlated at all. Even so, the use of genetic diversity seems to be the key to sustaining and improving wheat varieties. The genetic variation within specific wheat genotypes that allows them to grow and yield under heat and drought stress conditions, highlights the importance of identifying traits for drought and heat tolerance, disease resistance, and high nutritional quality; hence, landraces including drought-tolerant genes that have been naturally selected over time, are a source of desirable genes for better adaptation to climate change, being a promising way to increase gene flow.

On the other hand, wheat cultivars' phenology (especially crop cycle) plays an important role, modulating their tolerance to climatic variations regarding yield maintenance. Thus, days to flowering or days to maturity have an important relationship with wheat yield and are strongly influenced by temperature. However, it is important to stand out that, in a scenario of climate change with increasing temperatures, days to maturity are more severely affected than days to flowering, reducing considerably the grain-filling period and shortening, to a greater extent, the grain yield [24]. However, another important genetic trait should be taken into account regarding the relationship between wheat yield-phenology-climate change: CO2 presence influence. It has been studied that higher CO2 level in the environment significantly affects the tolerance of wheat to heat, maintaining or slightly reducing (<10%) wheat yield with a proposed temperature increase.

In this research, three decades of wheat (numerous genotypes) data are studied to determine the relationship between climate change, especially rainfall patterns and temperatures in winter and spring, grain yield and wheat phenology.

## 2. Material and methods

### 2.1 Wheat germplasm

This study was performed during 33 years with 299 field trials and an average of nine trials per year. The germplasm used were bread wheat genotypes with Portuguese and CIMMYT (International Maize and Wheat Improvement Center by its initials in Spanish) origins (parental) and predominantly spring types, even when some of them were facultative. To perform the analyses, from each field trial, were selected the five most yield productive genotypes.

### 2.2 Environmental conditions and field experiments

Data collection comprises the grain yield, test weight, TGW (Thousand Grain Weight) and phenological data (days to heading – DTH) from 1991 to 2024.

Field experiments were conducted in the region of Alentejo, in Portugal, which is considered the most important area in Portugal for bread wheat crop. Daily climatic data of the area (rainfall, minimum temperature and maximum temperature) were taken from the weather station whose GPS coordinates are: $38^0$53′03.4"N, $7^0$08′22.0"W, located in one of the farms used to grow most of the experiments, with no more than nine kilometers of the furthest farm (**Figure 1**).

According to the Food and Agriculture Organization (FAO, https://www.fao.org/soils-portal/data-hub/soil-classification/en/), soils in the wheat sowing area are classified as vertisols, ranging the pH between 6.8 and 7.8, showing a low organic matter content (< 1.6%), and presenting high contents of P (>200 ppm P2O5) and Ca (circa 3500 ppm Ca), and medium-high K content (between 68 and 168 ppm for K2O).

Each plot comprises six rows, 6–8 m long each (**Figure 2**), 20 cm apart, and harvest was carried out using a 1.5 m wide Nurserymaster Elite Plot Combine. Usually, all


**Figure 1.**
*Elvas region in Alentejo (Portugal); two main locations for the experiments along the years of the study (up). National plant breeding station in Elvas in a Google Earth view in 2023 (down). https://earth.google.com/*

**Figure 2.**
*Pictures of the experiments in the national plant breeding station.*

treatments were fertilized by adding 40–42 UN at sowing time and three top-dressed fertilizations (40 tillering – 60 booting - 40 heading/flowering). Weed controls were applied twice, at pre-emergence and post-emergence, and, when necessary, two antifungal treatments (stem elongation (Growth sstage-GS30-GS33) and booting (GS41-GS47)) were applied. Agricultural management also included conventional tillage treatment with moldboard plowing and disk harrowing at the beginning of the season and vibrating tine cultivation to prepare the seedbed before sowing. The seeding rate ranged between 350 and 400 g $m^{-2}$ and sowing dates were properly recorded annually, being the earliest sowing date 13/11 (in 2001) and the latest 25/01 (in 2023).

### 2.3 Measurements

During the wheat life cycle, both plant height (cm) and DTH were recorded. After the wheat harvest grain yield, TGW (in grams) and test weight (kg $hl^{-1}$) were also taken, as well as total N content in grain by means of NIRs technology, but only from 2002 on. Protein content (%) was obtained by multiplying the total N content by 5.7 [25].

### 2.4 Statistical analyses

Temporal trends in climatic variables were assessed following a Theil-Sen regression. Visual exploration of the data showed non-linear trends between response variables (grain yield, thousand-grain weight, test weight, and N content) and predictors (i.e., year of sowing, date of sowing and climate variables). GAMs were used to account for these non-linear relationships [26]. To assess potential interactive effects between date of sowing and climate, the interaction between both types of variables was tested in the model. The date of sowing was measured as the number of days lasting since November 1 for each year. Climate variables (average minimum and maximum temperatures and cumulative rainfall) were calculated for winter (December, January and February) and spring (March, April and May). Models were fit using reduced maximum likelihood (REML) and non-informative smooths were manually penalized one by one, refitting the model each time. After selecting the most parsimonious model, variables concurvity and model fit were assessed. All analyses were conducted in R v4.4.2 [27].

## 3. Results

Our results showed significant temporal trends in climate variables during the period studied (**Figure 3**). Maximum winter (December, January and February) and minimum spring (March, April and May) temperature significantly increased at a rate of 0.03 and 0.02°C $year^{-1}$, respectively. Maximum temperatures in spring tended to increase marginally, while minimum temperature in winter fluctuated enormously, showing differences of more than 3°C in consecutive years on several occasions. Regarding the rainfall, winter rainfall mainly ranged between 70 and 250 mm (24 out of 33 years were in this range), with 4 years with extremely low values (< 50 mm), while spring rainfall range was narrower, with almost all years between 50 and 200 mm. No temporal trends were observed for rainfall.

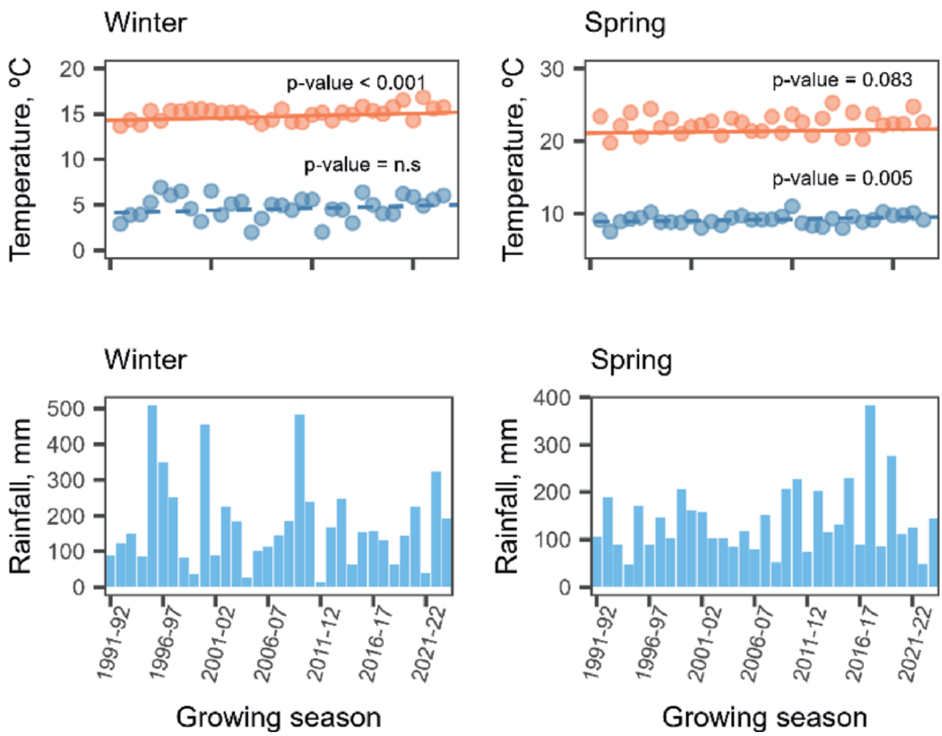


**Figure 3.**
*Winter (left-up) and spring (right-up) maximum and minimum temperature, and winter (left-down) and spring (right-down) rainfall diagrams of the 33 years of study in the experimental area. Solid lines represent significant temporal trends following the Theil–Sen approach.*

The temporal dynamics of the studied variables are presented in **Figure 4**. Regarding grain yield, it is observed that this variable shows an increasing tendency along the years of the experiments, only interrupted by a substantial valley noticed between the years 2000 and 2010. A similar evolution is observed in TGW, with a decrease in the recorded data of this variable during the first decade of the twenty-first century (**Figure 4**). However, test weight shows a clear increase up to the year 2000, when the growth stabilizes, with the values really close to 83 kg $hl^{-1}$. Regarding the protein, a linear growth is observed in the data, starting in values lower than 10% in the mid-1990s and finishing in the last years of the study in values above 15% (**Figure 4**).

Wheat yield was influenced by maximum temperature, both in winter and spring, with a negative effect (**Table 1**). Including the sowing date in the model, wheat grain yield was highly influenced by the interaction of winter rainfall and sowing date. Thus, **Figure 5** shows how November (early) and December (medium) sowings were barely influenced by winter rainfall, while January (late) sowings produced a reduction of yield when winter rainfall was scarce. The model predicted a reduction of about 70% in yield in low winter rainfall (~40 mm), as compared to high winter rainfall (~250 mm), corresponding to the *10th and 90th* percentile.

Supporting the temporal dynamics results for test weight (**Figure 4**), only two of the studied climatic variables were significant: spring rainfall (p-value <0.001), which positively influences test weight, and winter minimum temperature when

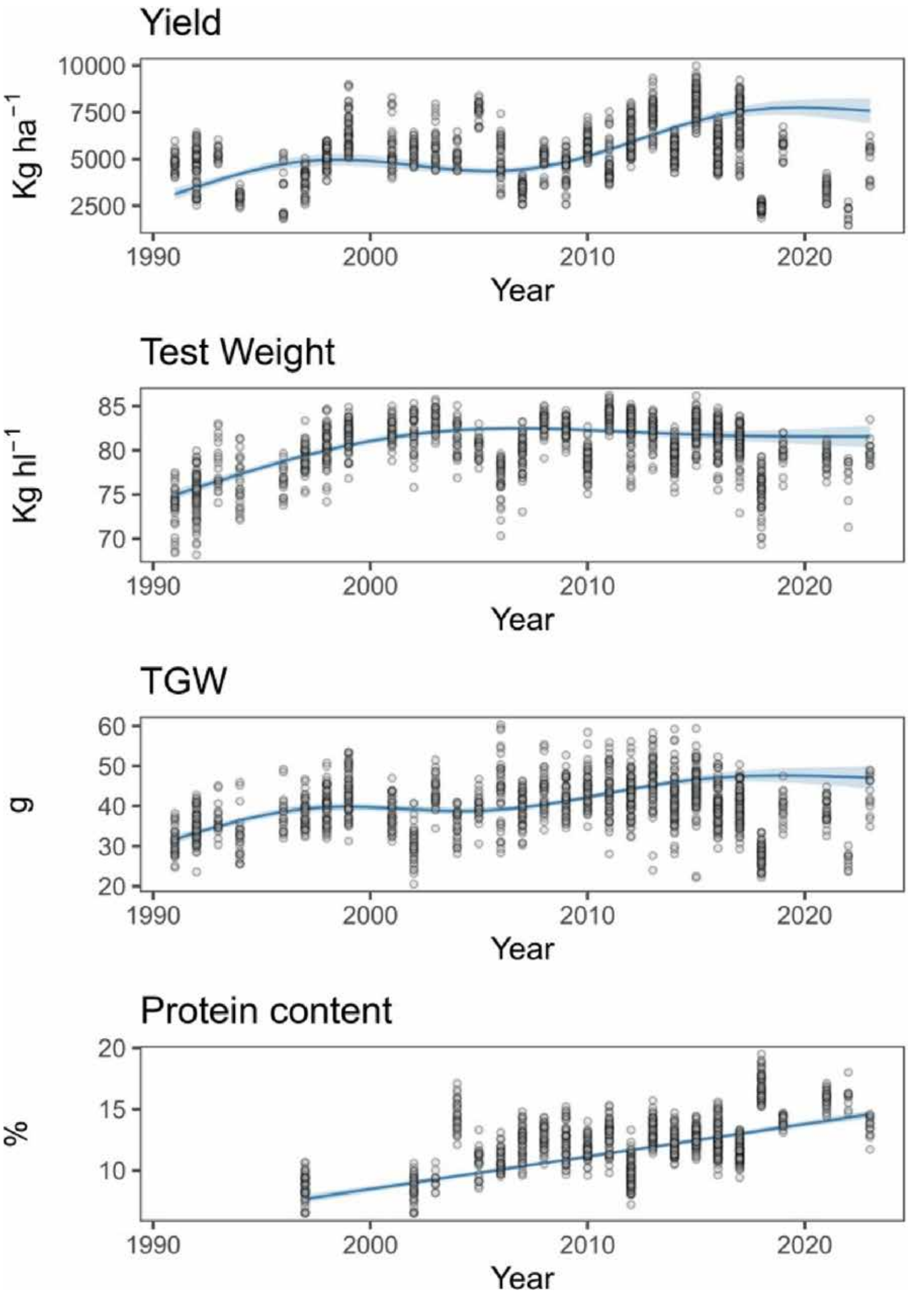


**Figure 4.**
*Temporal dynamics of wheat grain yield (kg ha$^{-1}$), test weight (kg hl$^{-1}$), thousand grain weight (g) and protein content (%) of wheat genotypes during 33 years of study in Alentejo region (Portugal).*

interacting with sowing date. **Figure 5** shows how early and medium sowing (November and December) barely affect test weight values in any type of winter (warm and cold; 10th and 90th percentile, respectively), while late sowing (January) can cause a decrease of about 50% in test weight when winter minimum temperatures are low (10th percentile). In the case of TGW, minimum and maximum spring

| Component | Term | Estimate | Std error | t-value | p-value |
|---|---|---|---|---|---|
| Parametric coefficients | Intercept | 22985.4 | 1206.3 | 19.1 | <0.001 |
| | Max. Temp. Winter | −640.1 | 72.8 | −8.8 | <0.001 |
| | Max. Temp. Spring | −357.8 | 19.5 | −18.4 | <0.001 |
| **Component** | **Term** | **edf** | **Ref. df** | **F-value** | **p-value** |
| Smooth terms | Interaction Sowing and Rainfall Winter | 6.5 | 7.3 | 120.7 | <0.001 |
| | Year of sowing | 4.0 | 4.0 | 268.0 | <0.001 |
| *Adjusted R-squared: 0.637, Deviance explained 0.642.* | | | | | |

**Table 1.**
*GAM Yield model showing the linear effect of maximum temperature in winter and spring and rainfall in spring and non-lineal effects of year of sowing and the interaction between date of sowing and precipitation on winter.*

temperature influenced it positively and negatively, respectively (p-value <0.001 in both cases). The interaction of minimum winter temperature with sowing date indicates the high sensitivity of TGW to a cold winter when late sowing (January) takes place (**Figure 5**).

Finally, spring rainfall negatively influenced the protein content, while winter rainfall positively affected it (p-value <0.001 in both cases). In case of the interaction of minimum winter temperature with sowing date, protein content seems to increase with late sowing in cold winters (**Figure 5**), showing about a 50% increase in protein content in a cold winter compared to a hot winter.

Regarding the phenological data, DTH was proven to be highly correlated in a negative way with the sowing date (**Figure 6**), which implies that the longer the sowing date, the shorter the DTH period, shortening, therefore, the period to generate biomass.

## 4. Discussion

Our results are in accordance with the literature regarding not only the irregularity in the rainfall patterns between years [28] but also the domination of the rainy months each year [29]. Thus, as González-Hidalgo et al. [29] previously stated for the Spanish mainland, in Portugal, rainfall distribution shows a clear dominance in autumn-winter regarding not only the amount (usually higher amount in winter than in spring) but also the irregularity, which greatly affects the behavior of wheat crop. Taking into account the data presented in **Figure 3**, the decrease in the yield and TGW could be explained by the small amount of winter rainfall in the first decade of 2000 years, combined with lower winter temperatures; the best example of this combination is the year 2004–2005, with averaged rainfall and minimum temperature in winter below 50 mm and 3°C, respectively.

In this regard, the recorded data for this study also confirms the previously stated by the literature, the increase of the temperature, both in winter and spring (about >1°C), and the broader irregularity regarding winter temperature (**Figure 1**) [30–32]. In their study, Asseng et al. [33] indicated that the increase in temperature negatively affects wheat yield, with an estimated reduction of 6% per Celsius degree of increment. However, most of the revised literature deals with the importance of spring temperature, especially what concerns to maximum temperature in late

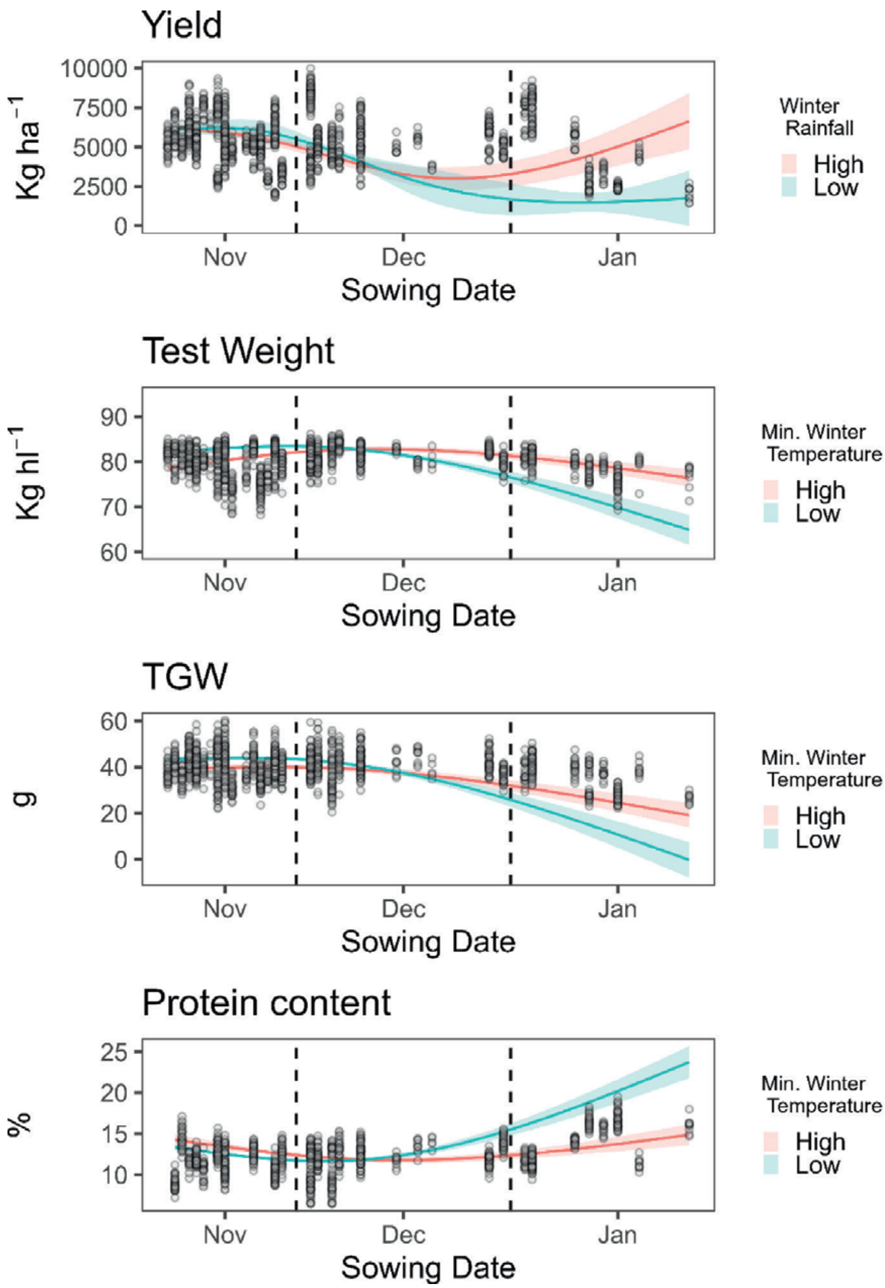


**Figure 5.**
*GAM results on grain yield (kg ha$^{-1}$) influenced by winter rainfall – sowing date interaction (up). Test weight (kg hl$^{-1}$), TGW (g), and protein content (%) influenced by the interaction minimum winter temperature – sowing date. Lines depict high and low winter rainfall and minimum temperature corresponding to 10th and 90th percentile of the climatic record during the studied period.*

spring or the date of the last spring freeze [34–37], but scarce literature deals with the importance of winter rainfall and temperatures, especially in the Mediterranean basin. In our case, even when spring rainfall and temperature were important predictors of grain yield (max. Temperature and rainfall), test weight (rainfall), TGW

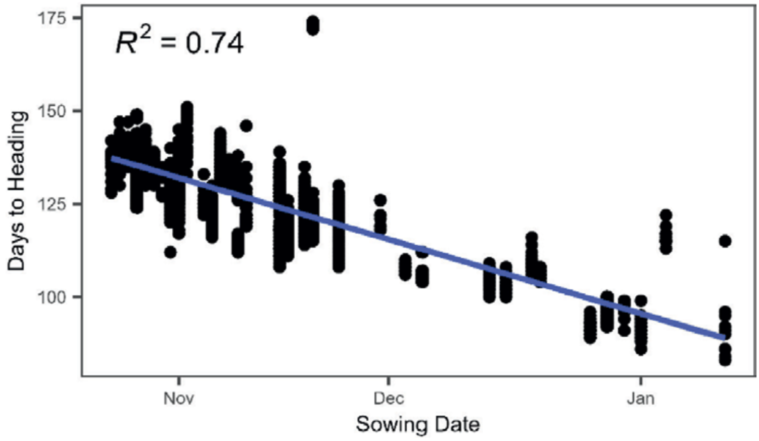


**Figure 6.**
*Correlation between days to heading and sowing date measured as the number of days lasting since November 1 for each year.*

(max. temperature) and protein content of the grain (max. temperature), the main factors affecting the studied parameters come from the winter. Thus, winter rainfall enormously influences grain yield, more than any other studied factor, as stated before (**Figures 4** and **5**), especially when late sowing takes place, bringing to light the great importance of winter rainfall and soil water accumulation for plant development during the spring season. In addition, minimum winter temperature determines, to a great extent, TGW, with an observed decrease in years with cold winter temperatures (**Figure 4**) and exacerbated in years with late sowing (**Figure 5**). This is probably due to slow plant growth in the first steps of the plant cycle, shorting importantly the period of time with appropriate temperature for the plant development; in Mediterranean areas, all the parameters that can compromise or highly influence vegetative growth have important consequences in the final yield of the crop, that is why all winter factors can severely influence final grain yield.

In the case of test weight, the more stable recorded data could be explained because test weight measures the adaptation capacity of a genotype to the environment where it is grown; in this sense, our data evidence that test weight is a more fixed value because it compensates the effects of the climate [38], while TGW, being one of the most important yield components, is highly dependent of the climatic season [39]. In addition, the heritability of the TGW trait is considerably higher than that of test weight in winter cereals [40].

Protein content is also influenced by rainfall and temperature, especially minimum winter temperatures, with a positive effect of colder winter on late sowing protein content. This is in accordance with the previously stated: the colder the winter is, the shorter the leaves formation, and so, the amount of assimilates necessary to maintain the foliage of the plant, which means the biomass. On the contrary, flag leaf and subsequent leaves, barely affected by winter cold, will create photo-assimilates to fill the grains, with no losses for biomass maintenance. With reference to protein content, it is well known that this variable is highly dependent on crop management, especially to N application (product, rate, timing, etc.) [41, 42].

Talking about crop management, interestingly, in our results, regarding the interaction of winter rainfall and sowing date, the highest yields were found with late sowing in rainy winter (90th percentile); this fact led us to think that by using irrigation systems, rainy winter can offer the best results in yield, even with late sowing. This fact is really interesting because late sowings can reduce the risk of eventual accidents in the field (storms, drought, diseases, late frosts, etc.) and can also reduce the use of herbicides during the cropping, decreasing both environmental pollution and crop incomes. However, it is necessary to take into account that in Mediterranean winter cereal systems, maturation occurs mostly on similar dates irrespective of the sowing date, and this is due to maximum spring temperatures, which accelerate maturation. In this regard, a late sowing date implies a shorter DTH period, with the resultant reduction in the vegetative period. A reduction of the vegetative period can decrease both leaf area index and root size, causing a reduction in the grain filling and so affecting negatively gross primary production. The decrease in gross primary production is observed in this study by means of yield (**Table 1**) and TGW reduction, similar to what was previously stated by Gitelson et al. [43].

## 5. Conclusions

To sum up, winter rainfall patterns and, especially minimum winter temperatures influence in a very important way wheat phenology and grain yield in the Mediterranean area, even more than the same parameters in spring. Sowing date interaction with winter rainfall can be used as a predictor of grain yield, while TGW is more influenced by sowing date interaction with minimum winter temperature. In the context of winter maximum temperatures increasing, late sowing (January) date could be a good practice to wheat growing under irrigation without compromising grain yield.

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## Conflict of interest

The authors declare no conflict of interest.

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Chapter 5

# Regional Variability in Mycotoxin Contamination of Brazilian Wheat: Implications for Food Security and Management Strategies

*Waldir Cintra de Jesus Junior, Eliana Badiale-Furlong, João Paulo Agapto, Duane Nascimento Oliveira, Flávio Sergio Afférri, Alberto Luciano Carmassi, Giovanna Lorena Silva Zanni, Maria Antonia Calori and Priscila Tessmer Scaglioni*

**Abstract**

This chapter critically examines the impact of Brazil's diverse agroecological regions on the incidence of mycotoxins in wheat, considering the implications for food safety and public health. Brazil's major wheat-producing regions—including the subtropical South, temperate Southeast, semiarid Midwest, and nascent areas in the humid Northeast—exhibit distinct climatic and agronomic conditions that drive regional differences in fungal pathogen prevalence and mycotoxin profiles. Focusing on key mycotoxins like deoxynivalenol (DON) and zearalenone (ZEN), the chapter elucidates how variations in temperature, humidity, and soil moisture regimes influence fungal colonization and toxin synthesis. Integrated management practices, such as targeted crop rotation, real-time climate monitoring, and deployment of resistant cultivars, are discussed as critical mitigation approaches. Through a comprehensive regional analysis, this chapter emphasizes the necessity for location-specific strategies to minimize mycotoxin contamination, thereby promoting sustainable wheat production and reinforcing food safety standards in Brazil.

**Keywords:** food safety, mycotoxin contamination, fungal pathogens, Brazilian wheat production, integrated management practices

## 1. Introduction

Wheat (*Triticum aestivum* L.), a staple crop that has co-evolved with human civilization, remains one of the most critical sources of carbohydrates in the global diet. It serves as the foundation for a wide array of food products, including steamed buns, sandwiches, pasta, dumplings, pizza, biscuits, puffs, and doughnuts, all of which are consumed daily across diverse cultures. However, wheat grains are highly susceptible to contamination by naturally occurring mycotoxins, produced by toxigenic fungi that colonize crops during both pre- and postharvest stages [1]. Due to their chemical stability, mycotoxins persist throughout food processing, allowing them to infiltrate the food production chain, thereby posing significant food safety concerns. The most prevalent mycotoxins associated with wheat grains include deoxynivalenol (DON), nivalenol (NIV), zearalenone (ZEN), ergot alkaloids (e.g., ergotamine), ochratoxin A (OTA), aflatoxins (Afla), and citrinin (CIT). Among these, DON and ZEN are the most frequently detected contaminants in wheat worldwide, representing a persistent challenge for food security and public health [2, 3].

The consumption of food products contaminated with mycotoxins poses a significant threat to both human and livestock health, compromising the safety and marketability of agricultural commodities [4]. Current estimates indicate that over five billion individuals worldwide are chronically exposed to mycotoxins through various, often unidentified, pathways, inadvertently ingesting contaminated food on a daily basis [3]. The ingestion of these toxic secondary metabolites can result in a spectrum of adverse health effects, collectively termed mycotoxicoses, which range from acute intoxication to chronic conditions with carcinogenic, hepatotoxic, nephrotoxic, and immunosuppressive consequences (**Figure 1**).

Reference [5] published a mini review of mycotoxin's occurrence in food in South America from 2018 to 2023, identifying research gaps and challenges in an era of

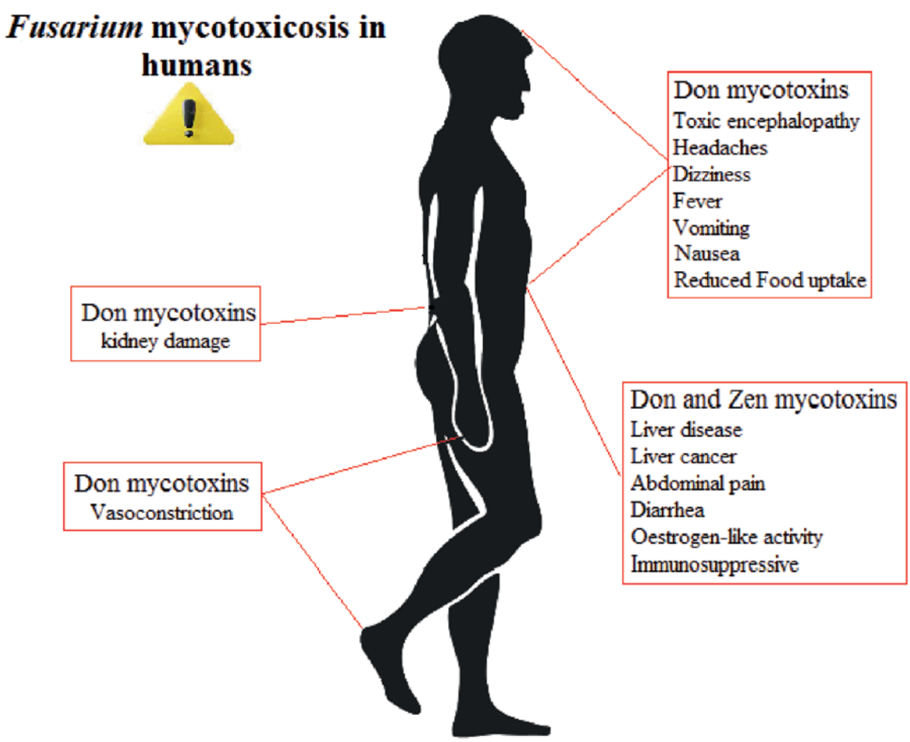


**Figure 1.**
*Spectrum of adverse effects caused by* Fusarium *spp. mycotoxins in humans.*

climate change. It was analyzed 53 studies, 21 from Brazil. Most of the mycotoxins analyzed were the traditional and regulated mycotoxins, with variable occurrences depending on the region, climatic conditions, and methodology used. Emerging and modified mycotoxins have only been studied in Argentina and Brazil, where some studies have shown high occurrences.

A review concerning actual status and future concerns of fungal mycotoxins in food commodities was published by reference [6]. Authors summarized the findings of 30 years of research into mycotoxins in major commercial food crops including wheat, maize, sorghum, pearl millet, peanut, oat, pulses, barley, oilseeds, rice, and fruits and fruit juices. They concluded that to eliminate or decrease levels of mycotoxin in food commodities below consumption levels, chemical, physical, biological, and eco-friendly strategies need to be used.

## 2. Mycotoxins in wheat and their importance for food safety

Wheat is one of the most widely cultivated cereals in the world, making up about 30% of global grain production. It is the third most planted crop, surpassed only by corn and rice. Together, these three cereals provide approximately 60% of the calories and 56% of the plant-based proteins consumed worldwide [7].

The quality of wheat grains is influenced by both biotic and abiotic factors, affecting their productivity and the nutritional value of the flour [8]. Fungal diseases, in addition to reducing yield, can produce mycotoxins, toxic compounds that impact food safety. For this reason, regulatory bodies like WHO and ANVISA set maximum limits for mycotoxins in grains and their derivatives [9].

Mycotoxins are secondary metabolites produced by toxin-forming fungi in response to environmental factors and interactions with the host. Their toxicity is linked to the inhibition of protein synthesis and mitochondrial dysfunctions, leading to adverse effects such as immunosuppression, neurological disorders, and reduced hematological and metabolic parameters [10]. Understanding the interaction between fungi, hosts, and the environment is essential to mitigate the impacts of mycotoxins in

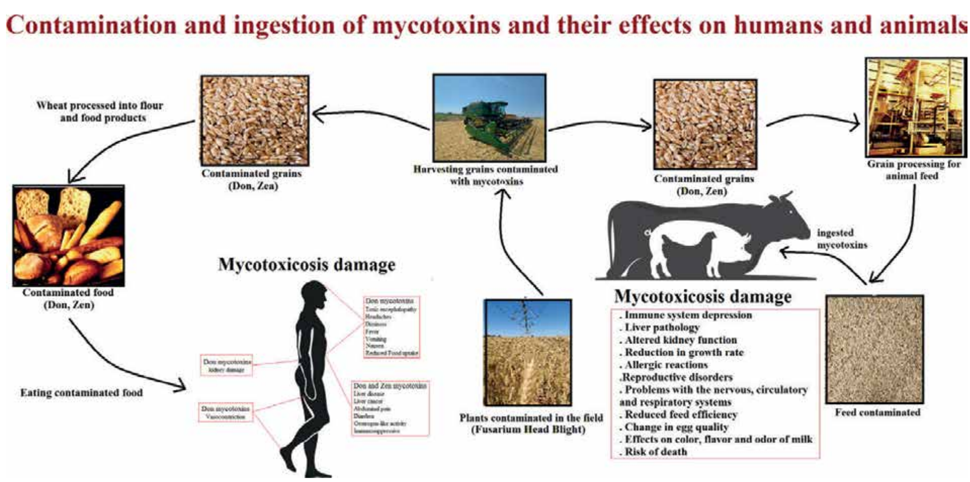


**Figure 2.**
*Possibles effects of contamination and ingestion of mycotoxins by humans and animals.*

the wheat production chain. **Figure 2** presents a conceptual illustration of the possible effects of contamination and ingestion of mycotoxins by humans and animals.

## 3. Regional distribution of wheat production in Brazil

Historically, wheat in Brazil was predominantly cultivated in the South Region, with Paraná and Rio Grande do Sul being the main producers. However, advances in genetic improvement have allowed the expansion of wheat cultivation to the Midwest and Southeast, a phenomenon known as the tropicalization of Brazilian wheat.

In 2024, the areas planted with wheat in Brazilian states, measured in hectares ($ha^{-1}$), were: Paraná (1,146,200), Rio Grande do Sul (1,131,013), Minas Gerais (143,974), São Paulo (123,720), Santa Catarina (122,577), Mato Grosso do Sul (44,496), Goiás (36,502), Bahia (6000), and the Federal District (5,3), totaling 2,959,755 $ha^{-1}$. Brazil ranks 14th in the world for wheat production [11]. The growth of wheat farming is linked to the increasing food demand and the multiple uses of wheat, making it a strategic crop for generating income. Additionally, wheat occupies idle land during the off-season, adapting to conditions with less rainfall and mild temperatures, providing ground cover and ensuring supply to the consumer market (**Figure 3**) [12].


**Figure 3.**
*Regions bordering on adaptability and wheat cultivation in Brazil.*

## 4. Main fungal pathogens and mycotoxins associated with wheat in Brazil

Diseases are one of the biggest challenges to wheat productivity in Brazil. Fusarium head blight (*Gibberella zeae* Petch (Schwein.) / *Fusarium graminearum* Schwabe) is the most destructive, potentially causing severe losses if management measures are not taken. Alongside the reduction in productivity, it compromises grain quality due to the production of mycotoxins, which pose risks to human and animal health [13].

In the wheat-growing regions, various species from the *Fusarium graminearum* complex (FGSC) stand out, including *F. acacia-mearnsii*, *F. aethiopicum, F. asiaticum, F. austroamericanum, F. brasilicum, F. graminearum, F. meridionale*, and *F. vorosii*. The main mycotoxins produced by Fusarium spp. are zearalenone (ZEN), deoxynivalenol (DON), and their acetylated chemotypes: 15-acetyl-DON (15-ADON), 3-acetyl-DON (3-ADON), and nivalenol (NIV). Trichothecenes are the most frequent contaminants in wheat and its derivatives [14].

Disease cycle of *Fusarium graminearum* and symptoms of Fusarium Head Blight (FHB) on wheat spikelets and kernels is presented in **Figures 4**–**6**. The impact that the fungus has on wheat crops is clear.

Besides *Fusarium* spp., other fungal genera like *Myrothecium*, *Caphalosporium*, *Verticimospoium*, and *Stachybotrys* also produce DON. While *Fusarium* spp. produces it

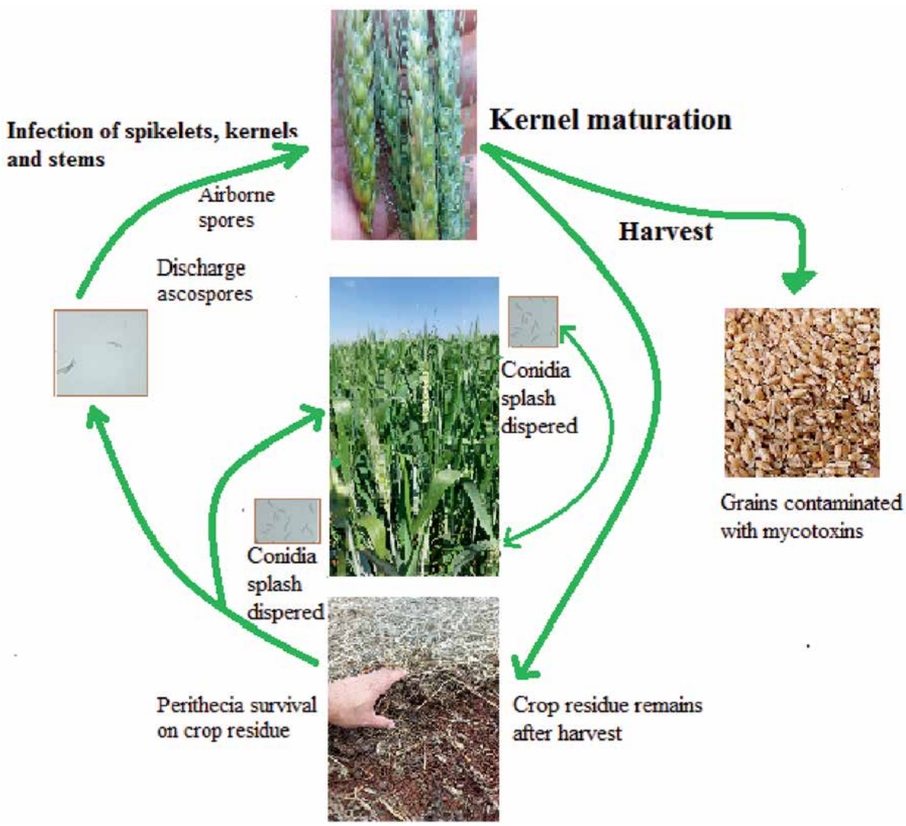


**Figure 4.**
*Disease cycle of* Fusarium graminearum *and symptoms of Fusarium Head Blight (FHB) on wheat spikelets, kernels, stems, and grains.*

**Figure 5.**
*Spikelets with the presence of macroconidia (pinkish color) of* Fusarium graminearum, *causal agent of Fusarium Head Blight (FHB).*

**Figure 6.**
*Spikelets with perithecia of* Fusarium graminearum*, causal agent of Fusarium Head Blight (FHB).*

during flowering and grain filling, the others can synthesize it pre- and postharvest. The main mycotoxins found in wheat include DON, NIV, ZEA, monoacetyl-deoxynivalenols (AcDON), fusarenone X (FUS), T-2 toxin (T2), diacetoxyscirpenol (DAS), and beauvericin (BEA). Acute symptoms of intoxication include nausea, vomiting, diarrhea, and fever, while the chronic exposure can affect the gastrointestinal and immune systems [15].

Contamination by mycotoxins in wheat is a challenge for food safety since they are stable during industrial processing and remain in the final products. To mitigate this risk, several countries set maximum tolerated limits. In Brazil, ANVISA's RDC No. 138/2017 defines restrictions for DON, ZEA, and fumonisins in cereals, including wheat [16].

Integrated management during pre- and postharvest is essential to reduce mycotoxin contamination. Measures include using resistant genotypes, applying fungicides based on epidemiological models, and good cultural practices. Moreover, there is a need to deepen the understanding of pathogen-host resistance and storage strategies to reduce contamination globally [17].

Conjugated mycotoxins pose another risk. DON can exist as deoxynivalenol-3-glucoside (D3G), whose ingestion releases DON during metabolism. Additionally, 3-ADON and 15-ADON can be converted into DON during digestion, increasing the toxicological risk [18]. The conversion of DON to D3G can occur due to climatic factors before harvest, along with the production of ZEA, an estrogenic metabolite of *F. graminearum* [19].

Furthermore, changes in climate systems suggest that slightly elevated $CO_2$ concentrations and interactions with temperature and water availability may stimulate the growth of some mycotoxigenic species, especially under water stress [19].

The impact of climate change will also be remarkable for soil microbial populations; these will be affected and subsequently will affect the prevalence of some fungi. Due to the changes of given fungal species to colonize new environments, the profile of toxigenic species occurring in different geographical areas could be modified, leading to new mycotoxin risks in specific regions [20].

## 5. Impact of Brazilian climate and agroecological diversity on the incidence of mycotoxins

Brazil has leveraged its climate diversity of equatorial, tropical, subtropical, temperate, and semiarid regions to become one of the largest producers and exporters of foods [18]. The geographical dimensions of Brazil result in various edaphoclimatic conditions, influencing crops and farming systems. However, just as climate diversity favors agricultural production, it also favors fungal growth and mycotoxin contamination. Climatic factors together with poor farming, harvest, and storage conditions increase the risk of and exposure to mycotoxins in food and feed.

In tropical regions, these differences create thermal and humidity variations (both in soil and air), especially at higher latitudes. With the expansion of wheat cultivation into the central-west and northeastern regions, as well as the south and southeast, wheat crops face different exposures and climatic influences. Variations in rainfall, temperature, and relative humidity favor the infection and development of fungal diseases that produce mycotoxins. Fusarium species are predominant in temperate and subtropical climates, especially under variations in temperature and humidity, and are more frequent in rainy years. Rainfall and mild temperatures during the flowering and maturation periods were shown to favor infestation of wheat with *F. graminearum* and *F. culmorum* and DON contamination [21].

The production of the mycotoxin DON is stimulated by rainy periods starting from the flowering of wheat, with less influence from water stress. In hot climates like Brazil's, *F. graminearu*m thrives at an average temperature of 25° and water activity above 0.88, while *F. culmorum* develops better at 21° and water activity of 0.87, making *F. graminearu*m more prevalent in warm climates. Other mycotoxin-producing fungi like *Myrothecium*, *Caphalosporium*, *Verticimospoium*, and *Stachybotrys* have a wide thermal range (0° to 35°), allowing their survival and infection in various regions. These conditions are common in Brazil, where lower latitudes have few climatic variations, such as in the Northeast and the center of the country, while at higher latitudes, there are well-defined seasons with cold, wet winters [22]. The effects of the climate on profiles of fungi and mycotoxins are challenges to ensure the availability of food safety [23–26].

Brazil has managed to improve the quality of food products prone to mycotoxin contamination. Stricter regulations and the use of GMP in harvest and storage have successfully improved food safety for exported and domestic products. However, it is essential to continue monitoring, to conduct additional risk assessments, and to educate consumers about the risk of mycotoxins in animal feed products [27].

## 6. Impact of mycotoxicological contamination in wheat

Wheat in Brazil is extensively studied regarding harvest management, geosystem, cultivation regions, plant selection, and biotic and abiotic factors affecting grain quality and quantity. A major challenge is fungal contamination along the food supply chain. The main producing regions, in the South and Southeast, have a subtropical climate, with cold and humid winters (10–15°C, 70–90% RH) [28, 29]. These conditions coincide with flowering and grain formation, increasing fungal contamination risk. Climate changes further complicate crop protection [29].

Classified grain-infecting fungi based on water and nutrient needs: *Fusarium* species (>20%) and *Aspergillus/Penicillium* (13–18%) as field and storage fungi. This broad classification aids risk management. Field infections depend on soil spores, atmospheric composition, water availability, microbial interactions, insects, pesticides, light, and harvest management. During storage, drying alters mycota, favoring xerophytic fungi. Milling reduces contamination in inner grain layers, as fungi are mostly external [29, 30].

Fungal species are identified *via* biological techniques, such as spore enumeration and isolation, followed by macroscopic/microscopic characterization. Molecular techniques identify species genetically and assess toxigenic potential [31].

Toxigenic fungi include *Fusarium, Aspergillus, Penicillium*, and *Alternaria*, producing mycotoxins under stress. While fungal growth and mycotoxin production share abiotic triggers, their thresholds differ, explaining weak correlations between fungal populations and toxin levels. This leads to multi-mycotoxin co-contamination in wheat. Although fungi can be inactivated during processing, mycotoxins persist due to their stable chemical structure [31].

Over 300 mycotoxins exist, but in food and feed grains, key families include aflatoxins (Afs), Alternaria toxins (AT), fumonisins (FUMO), ochratoxins (OT), trichothecenes (TCT), and zearalenone (ZEA), occurring in trace amounts. Exposure to these compounds causes mycotoxicosis, with symptoms like food refusal, headache, diarrhea, weight loss, neurological and immune disturbances, and cancer [10].

The effects of exposure to mycotoxins from diet have been studied. Different toxicological aspects and techniques have been considered to evaluate the damage (13, 16–31, 26–17, 32). The produced knowledge about the most frequent detected mycotoxins in cereals reinforces the agreement about the main action at molecular level and symptoms. The toxigenic genera, mycotoxins, targets, molecular actions, and toxic effects are detailed in **Table 1**.

| Fungi | Mycotoxins | Targets | Molecular effects | Symptoms |
|---|---|---|---|---|
| *A. flavus, A. parasiticus* | AFs B1, B2, G1, G2 | Liver | DNA adducts | Hepatose, Carcinogenese |
| *A. ochraceus, P. verrucosum* | OTA | Kidney | ATP Synthese | Nephrotoxicity |
| *F. verticilloides, F. proliferatum* | FUMO B1, B2 | Central Nervous System | Phospholipid metabolism | Neurological and respiratory damage |
| *F. culmorum* | ZEA | Reprodutive System | Estrogenic | Fertility reduction, abort |
| *F. graminearum* | DON, 3ADON, 15 ADON, D3G | Gastrointestinal and Immunological System | Inhibition of proteic synthese | Weight loss Immunological diseases. |
| *A. alternaria* | AT | Neurological System | cytotoxicity | Neurological disturbance |

*DON: desoxynivalenol, 3ADON: 3 acetyl desoxynivalenol, 15 ADON: 15 acetyl desoxynivalenol, D3G: 3 glycosil desoxynivalenol.*

**Table 1.**
*Fungi producer, mycotoxins, target, molecular effects and symptoms.*

Determining mycotoxin levels—whether from the same chemical family or different ones—is crucial for assessing health risks. These toxins vary in toxicity, both individually and as co-contaminants [26]. Thus, knowing their exact concentration or bioaccessibility is key to mitigating their impact.

Quantitative mycotoxin analysis requires careful sampling due to their random distribution, which can lead to false positives or negatives. Sample preparation is also critical, as masked mycotoxins—bound to the matrix or derived from host defense or processing—can still affect consumers. Identification and quantification rely on chromatographic methods (thin-layer, liquid, or gas chromatography) combined with UV-visible, fluorescence, diode array, or mass spectrometry detectors, enabling precise quantification even at low concentrations. Immunoassays, enzymatic activity tests, infrared sensors, and biochemical/electrical detectors exist but are less used due to their single-mycotoxin detection per assay and lack of official certification [32].

Mycotoxin contamination poses a significant challenge to global food security, exacerbated by climate changes that enhance fungal toxigenic potential. Ensuring food safety throughout the wheat production chain is crucial [26, 31]. Mycotoxicological risks persist across the grain chain, detectable through fungal or mycotoxin identification, either separately or simultaneously (**Figure 7**).

The soil is a critical factor as it may contain fungi, spores, nematodes, crop residues, nutrient imbalances, and climatic conditions that increase plant susceptibility to fungal infection and mycotoxin production [33]. During storage, the mycota shifts due to grain drying, replacing field fungi with xerophytic species. However, if mycotoxins are produced, they persist in the substrate. Toxigenic species from this new mycota may find favorable abiotic conditions to express their toxigenic potential. The processing stage reduces mycotoxin levels by removing the husk and decreasing granulometry. Baking, with or without fermentation, and thermal treatments contribute to mycotoxin degradation. In the digestive system, their bioaccessibility depends on their binding to indigestible matrix components. If absorbed, detoxification mechanisms promote excretion, minimizing harm. Thus, the chemical groups in

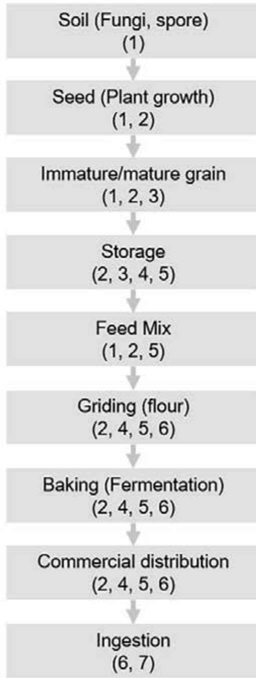


**Figure 7.**
*Food chain stages and the critical point to mycotoxicological contamination. 1. Fungi + spores; 2. Mycotoxins; 3. Mycota change; 4. Second mycota; 5. Mycotoxins; 6. Decontamination and degradation of mycotoxins; 7. bioacessibility.*

the contaminant, its form (free or bound), and exposure level determine its impact on consumer health, along with individual detoxification capacity [31, 32].

Trichothecenes, the most common mycotoxins produced by the *Fusarium* complex, have a basic structure composed of a tricyclic skeleton of cyclohexane and cyclopentane, with a double bond between carbons 9 and 10 and a uranic ring at positions 12 and 13. Methyl, hydroxyl, ester, acyl, and ketone groups can attach to carbons 3, 4, 7, 8, and 14. These variations classify trichothecenes into groups A, B, C, and D. Group B, characterized by a ketone group at carbon 8, is the most studied due to its high prevalence in food grains, particularly deoxynivalenol (DON) and its acetylated derivatives (3- and 15-acetyldeoxynivalenol—3ADON and 15ADON) [34].

## 7. Mycotoxicological contamination of wheat in Brazil

Damages of wheat crops caused by climatic parameters, insects and other plagues have been reported before the knowledge about impact of mycotoxins on grain quality. In Brazil, the reports about losses of wheat and other crops are also long-standing, but those specifically related to fungal contamination were highlighted in the decades 1970–1980. The main issues studied are summarized at the **Table 2**.

The most studied field fungi is the *Fusarium* complex that causes fusariose (**Table 3**), decreasing the productivity beyond the risk of production of mycotoxins, such as trichothecenes, zearalenone, fumonisins, and the emergent mycotoxins beuvericin and enniatins [31–34].

| Issue | Contributions | Region studied | Authors |
|---|---|---|---|
| Detection of wheat disease | Fusarium complex and its genetic characteristics | RS, P, SP | [35–38] |
| Management of the field | type of previous crops, type of irrigation and soil treatment | RS, P, SP | [39–41] |
| Combination of fungicides and stage of application | combinations of triazole fungicides during fluorescence and grain formation | RS | [41, 42] |
| Management of the storage | grain drying, silo hygiene, pesticide application | RS, SC | [43, 44] |
| Fungi and Mycotoxins in grains and derivates | Profile of Trichothecenes, ZEA and other mycotoxins | RS, SC, P, SP | [36, 45–50] |
| Processing effects on the level of mycotoxins | Milling parameters that affect the contamination levels | RS | [51–55] |
| Mitigation of grain contamination | Ozone and cold plasma | SP | [56–58] |
| Mitigation of mycotoxins in food ready to eat | Combinations of ingredients, fermentation and bakery stage to reduce bioaccessibility of trichothecenes and other mycotoxins | RS | [51] |

**Table 2.**
*Mycotoxicological studies in wheat and its derivatives.*

| Damage | Parameters | Producer Regions | Year |
|---|---|---|---|
| Generalized epidemic "white coup" | • Damage to grains,<br>• Crop losses<br>• Presence of *F. graminearum* | RS | 1976 |
| Losses due to septoria and FHB | • Rainfall data,<br>• Temperature,<br>• Variety | SP | 1976 |
| Seed infection and leaf spots | • Mycota | SP | 1980–1981 |
| Fungal disease | • Crop assessment<br>• Disease degree and intensity | SP | 1980–1981 |
| *Giberella zeae* | • Number of grains/ear<br>• % of gibberellated grains<br>• Climatic conditions | RS | 1981,1982, 1983 |
| Losses due to Gibberella | • Proposal of criteria for assessing losses | RS | 1984, 1985 |

**Table 3.**
*Longstanding Brazilian reports about damage to the wheat crop by fungus contamination.*

The aflatoxins and zearalenone were the mycotoxins determined in wheat grains damaged by fungal diseases or that caused mycotoxicosis in animals until the 1980s, as their detection was easier through thin-layer chromatography due to their fluorescent signal. Considering the worldwide concern about fungal disease in crops, two protocols were proposed for trichothecenes applicable to laboratories with basic infrastructure. The development of a simple and accessible thin-layer chromatography method for the simultaneous detection of T2-toxin, diacetoxyscirpenol, roridin, and verrucarin in feed and grain would be highly important for improving food safety and quality control. Reference [59] validated a thin layer chromatographic method to determine DON and applied it to evaluate the occurrence in 120 grain samples. The mycotoxin was detected only in two samples (183 μg/kg).

Reference [34] validated a gas chromagraphic method for simultaneous determination of diacetoxyscirpenol (DAS), T2 and HT2 toxin, T2 triol, T2 tetrahol, DON, and nivalenol (NIV) derivatized with heptafluorobutiryl imidazole, which detection limit varied from 0.1 to 0.5 mg/kg; median recovery 88% to A trichothecenes and 92% to B trichothecenes and variation coefficient from 2.8 and 12.9%. This protocol was applied to evaluate the occurrence of mycotoxins in wheat from experimental fields of São Paulo state and stored wheat grain in the silos of the Rio Grande city port, Rio Grande do Sul state. The aflatoxins B1, B2, G1, G2, esterigmatocystin, ochratoxin A (OTA), and zearalenone (ZEA) were also evaluated using thin layer chromatography. Fungi species were identified by morphological characteristics. Thirty percent of the samples from the experimental fields were contaminated with DON, DAS, NIV, toxin T2, and ZEA. In the stored grain were detected DAS, DON, T2 toxin, T2 tetrahol, and OTA [34, 60]. It is important to note that during this period, only aflatoxins had a maximum tolerable limit by Brazilian legislation, however they were not detected in the samples.

A pioneer study was carried out in Brazil (Badiale-Furlong, 1992) that determined the relation between biotic (height of the plants, percentage of fungal species) and abiotic parameters (temperature, relative humidity, monthly rainfall indices during the field period, latitude and altitude of the field) and trichothecenes levels found in wheat grain from experimental field by gas liquid chromatography. The results were evaluated by the probability of the relation between the dependent and independent variable be significant (F point) in a multiple regression. Despite the small number of samples and short sampling intervals, it was shown that the occurrence of each trichothecene was determined by multiple effects [34, 60]. The presence of DON, NIV e toxin T2 was predicted by relative humidity in the field. The pluviometry index, temperature along the flowering period, grain formation, and percentage of producer fungi allowed to obtain predictive equations of trichothecene occurrence with an error lower than 10%.

In the 1990 decade, global health authorities aimed to establish maximum acceptable limits for exposure to mycotoxins through diet. Brazilian authorities responsible for monitoring and establishing public health protection policies had difficulty for establishing mycotoxins limits in wheat and other commodities due to a lack of ongoing data about the prevalence and frequency of mycotoxins contamination. The routine of monitoring and legal control of the mycotoxicological quality of food and feed in grain production chains was limited by inaccessible analytical validated methodology and certificate laboratories, despite the evidence of the risk of mycotoxicological exposure to the diet shown by reports about fungal occurrences mainly in the commodities from the South region.

A survey of the occurrence of aflatoxins B1, B2, G1, G2, ochratoxin A, and zearalenone using thin layer chromatography was carried out on 79 samples of wheat products (flour, whole flour, and bran) sold in Rio Grande do Sul in 1997 and 1998. OTA was detected in wheat bran (18 ug/kg) and special wheat flour (26 ug/kg). ZEA (26 ug/kg) was detected in whole wheat flour. The frequency of contamination can be considered low (<3%), and no co-contamination of the mycotoxins was detected [49]. In comparison to the high-performance liquid chromatography method, the detection limits of this study can be considered high 1.9, 6.0, and 45 ug/kg, respectively, for AFLAs, OTA, and ZEA.

Reference [27] evaluated the occurrence of AFLs B1, B2, G1, G2, OTA, and ZEA and the physicochemical composition of 54 batches of wheat flour from 17 mills in the Southern region of Brazil. The authors found that 27% of flour samples sold as special did not meet the legal requirements for this class. Regarding the occurrence of mycotoxins, it was detected that 6% of the samples were contaminated with ochratoxin A and one was co-contaminated with zearalenone (12 and 53 ug/kg respectively). Statistical contrast analysis showed that the ash content was the component that better explained the presence of mycotoxins in the flours.

| Year/resolution | Products | AFs | DON | FUMO |
|---|---|---|---|---|
| 1976 / 34 | Foods | 30 (B1 + G1) | | |
| 2011/RDC 7 | Cereal and products | 5 | | |
| | Cereal-based food for infant feed | 1 | 200 | 200 |
| 2012 / RDC 7 | Whole wheat, kibbeh wheat, whole wheat flour, wheat bran | | 2.000 | |
| 2017 / RDC 138 | Wheat flour, pasta, crackers, crackers, and bakery products | | 1.750 | |
| 2017 / RDC 138 | Wheat for further processing | | 3.000 | — |
| | Whole wheat, kibbeh wheat, whole wheat flour, wheat bran | | 1.250 | |
| | Wheat flour, pasta, crackers, crackers, and bakery products | | 1.000 | |
| 2019 / RDC 138 | Whole wheat, kibbeh wheat, whole wheat flour, wheat bran | | 1.000 | |
| | Wheat flour, pasta, crackers, crackers, and bakery products | | 750 | |
| 2021 / IN 88 | Cereal-based food for infant feed | 1 | 200 | — |
| | Cereal and products | 5 | | |
| | Wheat flour, pasta, crackers, crackers, and bakery products | | 1.000 | |
| | Whole wheat, kibbeh wheat, whole wheat flour, wheat bran | | 1.250 | |
| | Wheat for further processing | | 2.000 | — |
| 2022 / IN 160 | Cereal-based food for infant feed | 1 | 200 | — |
| | Cereal and products | 5 | | — |
| | Wheat flour, pasta, crackers, crackers, and bakery products | | 1.000 | — |
| | Whole wheat, kibbeh wheat, whole wheat flour, wheat bran | | 1.250 | — |
| | Wheat for further processing | | 2.000 | 20 |

**Table 4.**
*Evolution of Brazilian maximum tolerable limits (MTL) for mycotoxins in wheat and its products.*

The effects of abiotic parameters on fungal diseases in wheat crops have been studied since the 1990s [34, 39, 50, 60] and remain a research focus, especially due to conflicting results regarding the influence of region, climate variation, field management, and other environmental factors on fungal diseases development.

These reports and others showing food contamination by fungi and mycotoxins, in the beginning of the XXI century, influenced the authorities to establish strategies to improve the analytical infrastructure of Brazilian laboratories and to propose maximum tolerable limits (MTL) for the main commodities and their products. The limits would be progressively reduced to allow the organization of protocols for reaching the legal limits without affecting the internal market and the food supply chain (**Table 4**). This context motivated the increase of research which target is mitigate the risk of exposure considering also the bioacessibility of the mycotoxins in wheat-based food ready to eat [51].

Data about the quality of the grains and crop damage by fungal contamination and their mycotoxins remain a concern because the method of evaluation are several, and sometimes the performance is not mentioned to allow a comparison among the information. Despite the controverse data, after the establishment of maximum tolerable limit for Afs, DON, OTA, and ZEA in wheat grains and their products for human consumption in Brazil, the information and studies about strategies to reduce exposure by mitigation protocols have improved.

Therefore, the established MTL, along with management and processing parameters, presents promising perspectives for preventing contamination and reducing the bioaccessibility of mycotoxins in wheat-based food [51].

## 8. Main strategies for managing the wheat disease complex aiming to mitigate mycotoxins

The main strategy for managing the wheat disease complex, particularly *Fusarium graminearum*, is the application of fungicides, which has been ramped up in recent years [61]. However, despite the increased use and even the number of applications (which can go up to three sprays per crop cycle), fungicides do not provide total (100%) effectiveness against the pathogen, meaning that wheat fields treated with fungicide can still become infected and contaminated with DON and other mycotoxins [33, 62].

Besides the issue of product effectiveness, the increased use of fungicides raises the likelihood of developing pathogen populations resistant to the main groups of products [33]. So, resistance to fungicides, stricter regulations for registration, and the slow development of new products are limiting the range of chemical classes of fungicides available. This leads to greater dependency on a smaller number of active ingredients with fungicidal action modes, consequently increasing the selection pressure for more cases of resistance. The limited availability of effective chemicals for plant protection, combined with the lack of genetically resistant varieties in major crops, has made key pathogens increasingly difficult to control. To extend the lifespan of the new fungicidal active ingredients currently available, integrated disease management strategies based on "smart" (i.e., guided) evolution of the pathogens are needed.

Although genetic resistance is the most economical, practical, and environmentally sound strategy, no wheat cultivar is immune to FHB and mycotoxins, meaning that many resistant cultivars can still become infected and accumulate DON concentrations above the permitted limits.

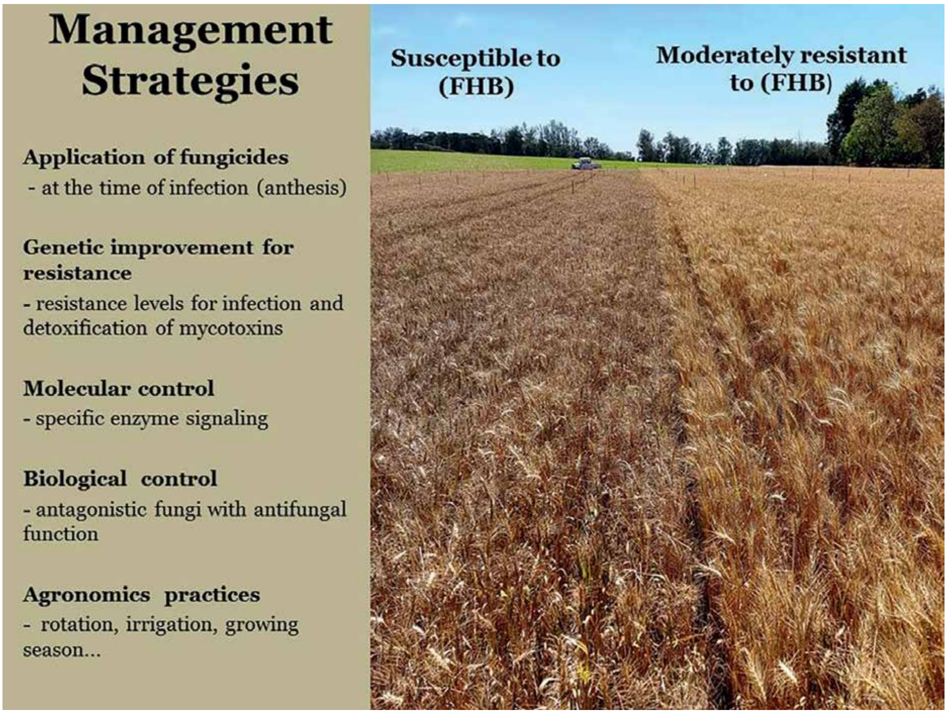


**Figure 8.**
*Key management strategies to Fusarium head blight (FHB) on wheat.*

The review of reference [20] presents management strategies to minimize mycotoxin contamination in wheat and its derivatives. Climate change and fungal resistance to fungicides are likely to worsen the issue. Food safety relies on understanding the factors influencing mycotoxin production, emphasizing trichothecenes and zearalenone. No single strategy is effective under conditions favorable to the pathogen, making it essential to integrate different approaches to mitigate mycotoxin production and ensure food biosafety [20].

Despite good crop management and processing practices, total decontamination is almost impossible [63]. Experimental evidence has shown that exposure to mycotoxins may be mitigated.

To effectively manage the fungal complex in wheat, it is essential to integrate chemical control with other strategies like genetic resistance, crop rotation, and cultural practices (**Figure 8**). This integration is extremely important for managing FHB [64] because no single strategy used in isolation leads to a satisfactory reduction in disease intensity and mycotoxin levels under conditions favorable for pathogen development.

## 9. Future challenges, potential research gaps, and policy recommendations to mitigate problems with mycotoxins on wheat

Future Challenges, Research Gaps, and Policy Recommendations for Mycotoxins in Wheat are presented in **Table 5**.

| Item | Factor | Effects |
|---|---|---|
| *Future Challenge* | Climate Change and Increased Mycotoxin Contamination | Rising global temperatures and changing precipitation patterns may expand the geographic distribution of mycotoxin-producing fungi, such as Fusarium spp., increasing wheat contamination risks.<br>Extreme weather events, such as prolonged droughts and heavy rains, can disrupt mycotoxin control measures. |
| | Emerging Mycotoxins and Co-Contamination Risks | While deoxynivalenol (DON) and zearalenone (ZEA) are well-studied, lesser-known mycotoxins (e.g., modified mycotoxins, emerging Fusarium metabolites) may pose new risks.<br>Co-occurrence of multiple mycotoxins in wheat complicates detection, regulation, and mitigation efforts. |
| | Limitations in Current Detection and Monitoring Systems | Variability in contamination across regions and wheat varieties necessitates more frequent, standardized, and cost-effective monitoring methods.<br>Smallholder farmers and regions with limited infrastructure may struggle to implement rigorous testing protocols. |
| | Trade and Regulatory Barriers | Stringent mycotoxin regulations in export markets (e.g., the European Union) could impact Brazilian wheat exports if contamination levels exceed permissible limits.<br>Differences in national and international regulatory frameworks create challenges for global trade and compliance. |
| Potential Research Gaps | Predictive Models for Mycotoxin Contamination | More accurate climate-driven models are needed to predict mycotoxin occurrence in wheat under different environmental scenarios.<br>Integration of remote sensing, IoT-based monitoring, and artificial intelligence (AI) could enhance early warning systems. |
| | Biocontrol and Sustainable Mitigation Strategies | Further research is needed on biological control agents, such as Bacillus spp. and Trichoderma spp., to reduce fungal infections in wheat fields.<br>Plant breeding and genetic engineering approaches should focus on developing resistant wheat cultivars. |
| | Post-Harvest and Storage Solutions | Studies on the effectiveness of innovative storage technologies (e.g., hermetic storage, ozone treatment) to reduce mycotoxin accumulation.<br>The role of microbiomes in controlling fungal growth and mycotoxin production in stored wheat. |
| | Toxicological and Health Impact Studies | More epidemiological data are needed to understand the long-term health effects of chronic mycotoxin exposure through wheat consumption.<br>Risk assessments should evaluate the impact of low-dose, long-term exposure, especially in vulnerable populations. |

| Item | Factor | Effects |
|---|---|---|
| Policy Recommendations | Strengthening Mycotoxin Monitoring and Surveillance | Establish a national surveillance program for mycotoxins in wheat, integrating rapid testing methods and blockchain-based traceability.<br>Encourage public-private partnerships to facilitate cost-effective testing for smallholder farmers. |
| | Standardizing Regulations and Compliance Measures | Align Brazilian mycotoxin regulations with international standards to facilitate exports and ensure food safety.<br>Implement stricter enforcement of maximum residue limits (MRLs) for wheat products in both domestic and export markets. |
| | Investment in Research and Development | Increase funding for multidisciplinary research on wheat mycotoxins, incorporating agronomy, food safety, biotechnology, and climatology.<br>Support innovation in alternative wheat processing techniques to degrade mycotoxins effectively. |
| | Capacity Building and Farmer Education | Develop training programs on mycotoxin prevention, early detection, and best agricultural practices for farmers, agronomists, and food processors.<br>Promote the adoption of Good Agricultural Practices (GAP), such as crop rotation, residue management, and fungicide optimization. |

**Table 5.**
*Future challenges, research gaps, and policy recommendations for mycotoxins in wheat.*

By addressing these challenges and research gaps with targeted policies, Brazil can mitigate mycotoxin risks in wheat, ensuring food safety, agricultural sustainability, and economic competitiveness.

## 10. Conclusion and future perspectives

- The chapter presented a summary of the main challenges and opportunities for controlling mycotoxin contamination in Brazilian wheat.
- It highlighted the importance of adopting a regionalized integrated management and science-based approach to tackle the serious issue of mycotoxin contamination.
- Strategies to reduce mycotoxin contamination of foodstuffs require a multifaceted approach combining pre- and postharvest interventions.
- It is crucial for research efforts to focus on monitoring the occurrence of mycotoxins in foods, evaluating population exposure, and understanding the prevalence of different toxigenic fungal species in various regions.
- Multidisciplinary efforts need to be made to improve the applicability of successful techniques in the wheat food supply chain to avoid mycotoxins' impact on global food insecurity
- Public policies and technological innovation are crucial to ensure the quality and safety of wheat produced in Brazil.

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Section 3

# Sustainable Management, Nutrition, and Policy Perspectives

Chapter 6

# Wheat as a Nutritional Powerhouse: Shaping Global Food Security

*Kusum Sharma and Pawan Kumar Sharma*

## Abstract

Wheat (*Triticum* spp.), known as the "golden grain," plays an indispensable role in global food security, providing approximately 20% of the world's protein and caloric intake. As a dietary staple for over 35% of the global population, wheat's high-yielding and disease-resistant varieties introduced during the Asian Green Revolution significantly transformed agricultural productivity. The major producers of wheat in 2022 were China, India, Russia, and the European Union, with a total production of about 778 million metric tons. Over 35% of the world's population depends on wheat as a staple meal. It serves as the leading source of plant-based protein, with a protein content of about 13%, higher than most major cereals. Additionally, biofortification programs have enhanced wheat's nutrient profile to combat malnutrition and hidden hunger, especially in impoverished regions. Wheat has an equally significant socio-economic impact because of its capacity to sustain millions of farmers and strengthen national economies through trade and employment. With an estimated $50 billion in worldwide trade, wheat is a crucial commodity for food security and international markets. The importance of whole wheat in sustainable agriculture is highlighted by initiatives to increase its consumption, enhance storage facilities, and lower post-harvest losses. There will be 10 billion people on the earth by 2050, so ensuring sustainable wheat production and equitable distribution is still crucial. Furthermore, despite climatic change and declining soil fertility, the study highlights wheat's economic importance, agronomic advantages, and nutritional worth.

**Keywords:** wheat, global food, food security, sustainable, hidden hunger, biofortification

## 1. Introduction

Wheat (*Triticum* spp.), belonging to the Poaceae (Gramineae) family, has been a cornerstone of human civilization for over 10,000 years [1]. Its versatility, adaptability to diverse climates, ease of storage, and high caloric and nutritional value make it a key player in addressing global food demands. Accounting for 20% of daily caloric and protein intake, wheat is a vital component of the human diet and ranks as the second-most significant food crop in developing nations after rice [2]. It supports food security for an estimated 80 million people worldwide. Traditionally, food insecurity has been addressed by increasing the production of cheap, high-calorie staple crops. However, the growing prevalence of micronutrient malnutrition necessitates a balanced focus on both staple crops like wheat and nutrient-rich foods. As a dietary staple for over 35% of the global population, wheat transcends cultural and geographical boundaries [3]. Rich in carbohydrates, dietary fiber, and essential nutrients, it contributes to human health and serves as a versatile ingredient in various food products.

Wheat cultivation also underpins the livelihoods of millions of farmers and supports agricultural economies globally. Bread wheat (hexaploid) accounts for 95% of global production while durum wheat (tetraploid), commonly known as pasta wheat, constitutes the remaining 5% [4]. Durum wheat thrives in dry Mediterranean climates and is used in bread, pasta, and regional cuisines like couscous and bulgar. Additionally, ancient wheat varieties such as einkorn, emmer, and spelt (collectively known as farro in Italy) continue to be cultivated in regions like Spain, Turkey, the Balkans, and the Indian subcontinent [5]. Modern wheat varieties are typically amber-colored, but colored wheat varieties rich in anthocyanins and other phytochemicals are gaining popularity for their health benefits [6, 7]. Purple wheat was developed in the nineteenth century, and blue wheat emerged in the twentieth century through interspecific crossbreeding of *Triticum aestivum* with wild wheat species like *Thinopyrum ponticum*, *Triticum monococcum*, and *Th. Bessarabicum* [8]. These advancements reflect the crop's genetic diversity, with approximately 25,000 varieties adapted to temperate climates [9]. Under optimal conditions, including adequate water, mineral fertilizers, and effective pest and disease control, wheat yields can surpass 10 tonnes per hectare, making it a preferred crop in temperate regions [10]. Harvesting methods include conventional practices and mechanical combine harvesters. Proper storage requires moisture content below 15% to prevent spoilage and pest infestation. Wheat's significance extends beyond nourishment, encompassing its critical role in global food security, agricultural economies, and human health [11]. Ongoing research and innovation in wheat breeding and cultivation will ensure its continued contribution to sustainable food systems.

Wheat occupies a central position in the history of the Asian Green Revolution, serving as a cornerstone of the agricultural transformations that reshaped the region's food systems [12]. During the mid-twentieth century, Asia grappled with recurring food shortages, malnutrition, and widespread hunger exacerbated by rapid population growth and limited agricultural productivity [13]. The Green Revolution, spearheaded by the introduction of high-yielding wheat varieties and modern agricultural practices, not only alleviated these crises but also laid the foundation for sustained food security. Wheat, as a nutritional powerhouse, emerged as a key driver of this transformation, ensuring caloric adequacy while addressing broader nutritional needs across the region [14]. The success of the Green Revolution in Asia was closely tied to the development and dissemination of improved wheat cultivars. These varieties, developed through advances in agronomy and plant breeding, featured enhanced resistance to diseases, adaptability to diverse agroecological conditions, and higher yield potential. Countries like India and Pakistan witnessed dramatic increases in wheat production, turning from food-deficient to self-sufficient nations within a decade [15]. Wheat's contribution to the daily caloric intake of populations was significant, providing approximately 500 kilocalories per capita daily in major wheat-consuming nations such as India and China [4]. This marked improvement in food availability played a pivotal role in reducing hunger and stabilizing economies.

Beyond its role in addressing caloric deficits, wheat's nutritional value underscores its importance in shaping global food security [16]. As a whole grain, wheat is a rich source of carbohydrates, protein, dietary fiber, and essential micronutrients such as iron, zinc, and B vitamins. The Green Revolution's focus on wheat not only enhanced the food supply but also provided a platform to combat malnutrition in regions where nutrient deficiencies were prevalent [17]. Wholegrain wheat consumption, in particular, is recognized for its role in mitigating the triple burden of malnutrition—undernutrition, micronutrient deficiencies, and overnutrition—highlighting its relevance in contemporary dietary strategies [18]. The Green Revolution's wheat-centered advancements also had far-reaching implications for agricultural sustainability and economic stability in Asia [19]. Investments in irrigation, fertilizers, and mechanization, combined with the cultivation of high-yielding wheat varieties, improved agricultural productivity and rural livelihoods [20]. These changes enabled millions to escape poverty, as the increased food supply stabilized markets and reduced the risk of food price volatility. However, wheat's dominance in agricultural systems also underscores the need for diversification to ensure resilience against climate change and evolving dietary needs.

## 2. Nutritional composition

Wheat grains are a rich source of macronutrients, including carbohydrates, proteins, and fats, as well as micronutrients such as vitamins, minerals, and phytochemicals [21]. They also contain total dietary fiber and bioactive compounds. In addition, colored wheat varieties are notable for their natural pigments, such as carotenoids and anthocyanins, which have health-promoting and disease-preventing properties [22]. Carbohydrates, which account for 60–70% of the wheat kernel, are primarily in the form of starch and serve as a major energy source in human diets, making wheat a key component of energy metabolism [23]. Proteins, the second-most abundant macronutrient, constitute about 12–15% of wheat's composition in common varieties [24]. Wheat proteins include gluten, a complex of glutenin and gliadin, which provides the unique elasticity and baking properties essential in bread-making [25]. While wheat is a valuable source of plant-based protein, its amino acid profile is not fully balanced and can be complemented with other foods for a nutritionally complete diet [26]. Fat content in wheat is relatively low, around 2–3%, and primarily concentrated in the germ portion of the kernel. These essential fatty acids contribute to energy and support cellular health [27]. With the global population projected to reach 10 billion by 2050, wheat remains critical for global food security [28]. Advances in wheat breeding for climate resilience, such as varieties tolerant to heat, drought, and pests, are essential to meet rising demands sustainably [29, 30]. Furthermore, promoting wholegrain wheat products can significantly enhance nutritional outcomes, especially in low- and middle-income countries where wheat is a dietary staple. Wheat's role in the Asian Green Revolution highlights its dual significance as a staple crop and a nutritional powerhouse, helping to mitigate food shortages while supporting economic development Van der Ploeg [31]. As global food systems face new challenges, continued research and investment in sustainable wheat production will ensure that its benefits extend to future generations (**Table 1**).

Wheat (*Triticum aestivum*) is a staple cereal grain that provides essential macronutrients, micronutrients, and bioactive compounds contributing to human health. Its nutritional benefits are as follows:

1. *Rich source of carbohydrates*: Wheat is primarily composed of complex carbohydrates, particularly *starch*, which serves as a major energy source. It has a

| Sr. no. | Nutritional component | Function in human health | Refs. |
|---|---|---|---|
| 1 | Carbohydrates | Provide energy for daily activities and bodily functions. | Poole et al. [18] |
| 2 | Protein | Essential for muscle repair, growth, and immune function; supports overall cellular processes. | Shiferaw et al. [4] |
| 3 | Dietary Fiber | Improves digestive health, regulates blood sugar levels, and reduces the risk of cardiovascular diseases. | Dixon et al. [32] |
| 4 | Iron | Prevents anemia, supports oxygen transport in blood, and is critical for cognitive development and physical growth. | FAO [29] |
| 5 | Zinc | Boosts immune function, aids wound healing, and supports cellular metabolism and growth. | Shiferaw et al. [4] |
| 6 | B vitamins | Vital for energy production, red blood cell formation, and maintaining healthy skin and brain function. | Poole et al. [18] |
| 7 | Antioxidants | Protect cells from oxidative damage and lower the risk of chronic diseases such as cancer and diabetes. | FAO [29] |
| 8 | Selenium | Strengthens the immune system and supports thyroid function. | Dixon et al. [32] |

**Table 1.**
*Nutritional components of wheat and their importance to human health.*

*low glycemic index* when consumed as whole wheat, aiding in sustained energy release and blood glucose regulation (**Table 1**) [33].

2. *Dietary fiber*: Whole wheat is a significant source of *dietary fiber* (10–15% by weight) Shewry and Hey [34]., including insoluble fiber (e.g., cellulose and hemicellulose) and soluble fiber (e.g., beta-glucans) [35]. Fiber supports gastrointestinal health, regulates bowel movements, lowers cholesterol levels, and enhances satiety (**Table 1**) [36].

3. *Protein content*: Wheat provides approximately *10–15% protein*, depending on the variety [37]. It contains *gluten*, a combination of gliadin and glutenin, which is essential for baking properties [38]. Although it is not a complete protein (low in lysine), combining wheat with legumes can compensate for amino acid deficiencies (**Table 1**) [39, 40].

4. *Micronutrients*:

- *Vitamins*: Wheat is a source of *B vitamins* (thiamine, niacin, riboflavin, and folate), which play key roles in energy metabolism, red blood cell formation, and nervous system function [39].

- *Minerals*: It provides essential minerals, like *iron, zinc, magnesium, phosphorus, and selenium*, which are important for oxygen transport, enzyme function, and bone health.

5. *Phytochemicals and antioxidants*: Wheat contains bioactive compounds such as *phenolic acids*, *flavonoids*, and *lignans*, which exhibit antioxidant properties [41]. These compounds reduce oxidative stress, protect against chronic diseases like cardiovascular disease, and have anti-inflammatory effects [42].

6. *Healthy fats*: Though present in small amounts, wheat contains beneficial *polyunsaturated fatty acids (PUFAs)*, including linoleic acid, which supports heart health [43].

7. *Weight management and diabetes control*: Whole wheat products have higher fiber and slower digestion rates, which promote satiety, assist in weight management, and regulate postprandial glucose spikes, making them beneficial for individuals with *diabetes* [44].

8. *Prevention of chronic diseases*: Regular consumption of whole wheat is linked to a reduced risk of *cardiovascular diseases*, *type 2 diabetes*, *obesity*, and certain types of *cancers* (e.g., colorectal cancer) due to its fiber, vitamins, and antioxidant content [45].

## 3. Agronomic importance and cultivation practices

Wheat (*Triticum aestivum*) offers several agronomic advantages, making it a vital crop for global food security [46]. Its wide adaptability allows it to thrive in diverse agroclimatic conditions, ranging from temperate to semi-arid regions, with a cultivation range spanning latitudes of 30–60° N and 27–40° S [47]. The crop thrives in a variety of agroclimatic zones, including temperate, subtropical, and semi-arid ones, demonstrating its exceptional adaptability. It is a flexible solution for a variety of locations because it can tolerate a large range of temperatures, from cold to hot climes. This versatility enables farmers to cultivate wheat in various soil types, including loamy and clay soils, provided they have good drainage. Wheat has a relatively short growing cycle, maturing within 90–150 days [48], which makes it highly suitable for crop rotation systems. Rotational cropping involving wheat helps in breaking pest and disease cycles, improving soil health, and maintaining soil fertility. Moreover, wheat cultivation enhances land use efficiency as it allows for multiple cropping within a single agricultural year [49].

In terms of climate resilience, wheat exhibits remarkable tolerance to diverse environmental stresses. Modern wheat varieties have been developed to withstand drought, heat, and frost stress, ensuring stable yields in the face of fluctuating climatic conditions. Wheat demonstrates a moderate water-use efficiency, making it suitable for *rainfed agriculture* in arid and semi-arid regions [50]. Under water-limited environments, the deep root system of wheat helps in accessing moisture from lower soil horizons, improving its drought resilience [51]. Additionally, wheat varieties with shorter life cycles can escape terminal drought and heat stress by completing their growth phases before extreme weather events. Breeding programs have further enhanced wheat's resilience by incorporating traits for *salinity tolerance* and resistance to common diseases such as rusts and blights, which are often exacerbated under changing climate scenarios [52]. As a result, wheat remains a crucial crop for ensuring food security in regions prone to climatic variability, offering both agronomic and economic advantages to farmers worldwide (**Table 2**).

| Sr. no. | Aspect | Agronomic advantages | Climate resilience benefits | Refs. |
|---|---|---|---|---|
| 1 | Adaptability | Grows in diverse agro-climatic zones, including temperate, subtropical, and semi-arid regions. | Tolerates a range of temperatures, from cool to hot climates. | Shoukat et al. [53] and Roy et al. [54] |
| 2 | Growing cycle | Short growing period (90–150 days), enabling multiple cropping systems. | Early-maturing varieties can escape terminal drought and heat stress. | Singh et al. [55] and Ghaffar et al. [56] |
| 3 | Soil suitability | Thrives in loamy and clay soils with good drainage. | Resilient under varying soil moisture levels. | AbdelRahman et al. [57 and Gooding and Shewry [58] |
| 4 | Crop rotation | Breaks pest and disease cycles, improves soil health, and maintains fertility. | Reduces soil degradation and enhances long-term soil sustainability. | Aslam et al. [59] |
| 5 | Water efficiency | Moderate water-use efficiency makes it suitable for rainfed agriculture. | Deep root systems improve drought resilience by accessing deeper moisture. | Osman et al. [60] and Lu et al. [61] |
| 6 | Stress tolerance | Suitable for low-input farming and marginal lands. | Enhanced resistance to drought, heat, frost, and salinity stress. | Roopnarain et al. [62] |
| 7 | Disease resistance | Breeding programs improve resistance to major diseases like rusts and blights. | Reduces yield losses caused by climate-induced pest and disease pressure. | Bhavani et al. [63] and Luo et al. [64] |
| 8 | Yield stability | Provides consistent yields across variable conditions. | Climate-resilient varieties ensure stable production under stress. | Bhandari et al. [65] and Ahmad et al. [66] |

**Table 2.**
*Wheat's versatility as a crop, its ability to thrive in diverse farming systems, and its resilience to climatic stresses, making it essential for global food security.*

## 4. Role in global food security

Wheat is one of the most vital staple crops worldwide, playing a crucial role in ensuring global food security due to its adaptability, nutritional value, and economic significance. As the second-most cultivated cereal after maize, wheat provides approximately 20% of the global population's caloric and protein intake [67]. This makes it indispensable for meeting the dietary needs of billions, particularly in developing countries. Wheat's ability to thrive in diverse agro-climatic regions contributes to its global accessibility, from temperate zones to semi-arid areas [68]. However, the growing demand for wheat, fueled by population growth and dietary shifts, has placed immense pressure on production systems. According to recent studies, global wheat production must increase by 50% by 2050 to meet projected food demand [69].

Wheat's resilience to environmental stresses is critical for sustaining yields in a changing climate. Advances in breeding for drought- and heat-tolerant wheat varieties have shown promise in mitigating the adverse effects of climate change. However, the increasing frequency of extreme weather events poses challenges to achieving consistent yields, particularly in regions prone to drought, such as Sub-Saharan Africa and South Asia [70]. Furthermore, wheat is a significant source of essential nutrients, including dietary fiber, B vitamins, and minerals like magnesium and zinc, which are vital for combating malnutrition and micronutrient deficiencies. Fortification programs and biofortified wheat varieties, such as those enriched with zinc, have demonstrated their potential to address hidden hunger in resource-limited populations [71].

Despite its critical role in food security, wheat production faces several challenges, including declining soil fertility, pests, diseases, and unsustainable farming practices. Innovations in precision agriculture, conservation tillage, and integrated pest management are pivotal for enhancing wheat productivity [72] while minimizing environmental degradation [73]. Furthermore, policy interventions and international collaboration are required to stabilize global wheat markets, reduce post-harvest losses, and ensure equitable access to this essential crop. By addressing these challenges and leveraging innovations, wheat can continue to be a cornerstone of global food security in the coming decades (**Figure 1**).

### 4.1 Global wheat exports

Over the past 5 years, global wheat exports have experienced notable fluctuations due to factors such as production levels, international demand, and geopolitical events. From the 2019/2020 to the 2023/2024 marketing year, wheat exports have increased by approximately 21%, showcasing a consistent upward trend. The global wheat export volume was recorded at 183.6 million metric tons in 2019/2020, rising to 222 million metric tons in the 2023/2024 marketing year [74]. This upward trajectory highlights wheat's growing demand as a staple food for a significant portion of the world's population.

In 2023/2024, US wheat milling hit its lowest level since 2014/2015, and exports dropped to their lowest since 1971, challenged by a strong dollar and Black Sea

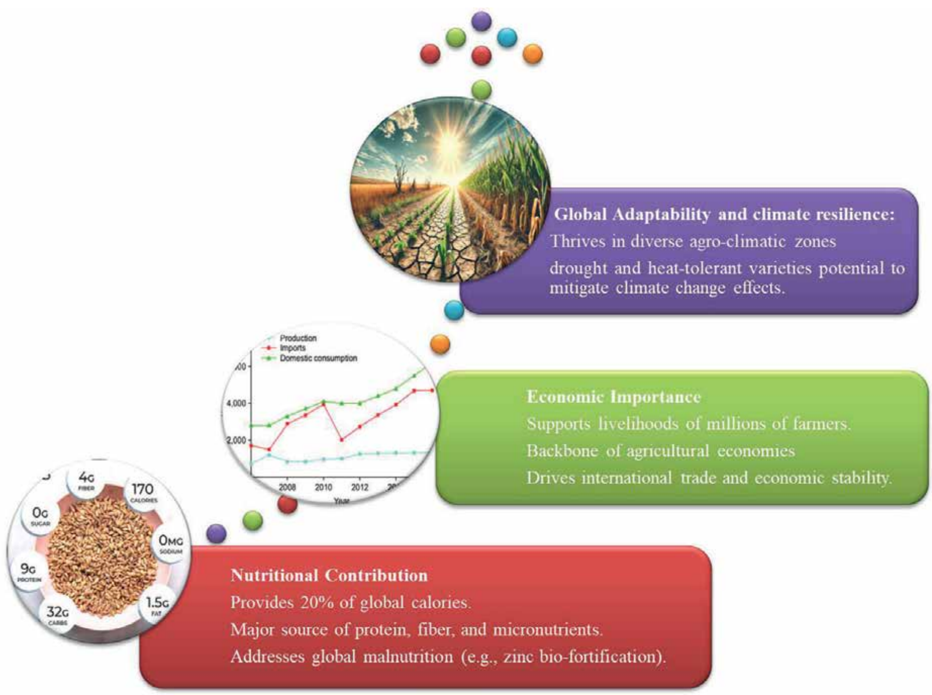


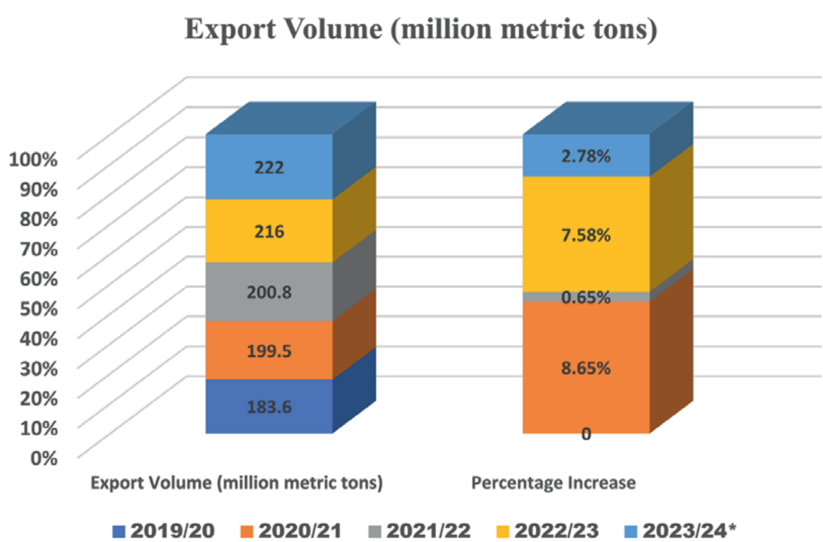

**Figure 1.**
*Importance of wheat in different areas.*

competition. However, hot, dry conditions in *Southern Russia* could jeopardize global wheat surpluses, potentially improving US wheat price prospects in 2024/2025 (**Figures 2** and **3**).

### 4.2 Leading wheat exporting countries (2023/2024)

Russia has emerged as the leading wheat exporter, contributing 51 million metric tons in 2023/2024, followed by the European Union (36.5 million metric tons), Australia (27.5 million metric tons), Canada (26 million metric tons), and the United States (20.5 million metric tons) [74]. These key exporting nations play a significant role in the global wheat market, meeting the food demands of importing countries and ensuring food security worldwide. Wheat is an essential crop, providing about 20% of the world's food calories and protein, making it integral to global diets and nutrition [75].

The economic importance of wheat exports is substantial, contributing significantly to revenue generation, employment, and trade balance. For example, in 2023,




| Marketing Year | Export Volume (million metric tons) | Percentage Increase |
|---|---|---|
| 2019/20 | 183.6 | - |
| 2020/21 | 199.5 | 8.65% |
| 2021/22 | 200.8 | 0.65% |
| 2022/23 | 216.0 | 7.58% |
| 2023/24* | 222.0 | 2.78% |

**Figure 2.**
*Global Wheat Export Volumes (2019/2020–2023/2024). *Projected data for 2023/2024. These figures indicate a consistent upward trend in global wheat exports, with an approximate increase of 21% from the 2019/2020 to the 2023/2024 marketing year.*

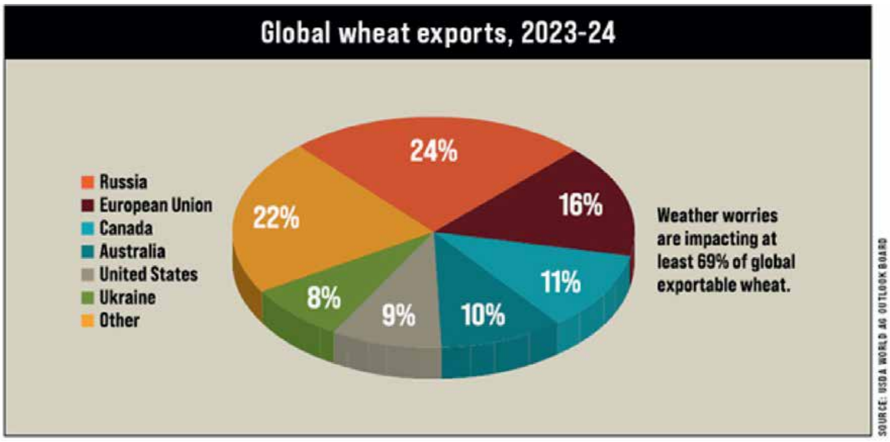



**Figure 3.**
*Global wheat exports in the year of 2023–2024. https://www.farmprogress.com/commentary/wheat-prices-revived-on-weather-woes*

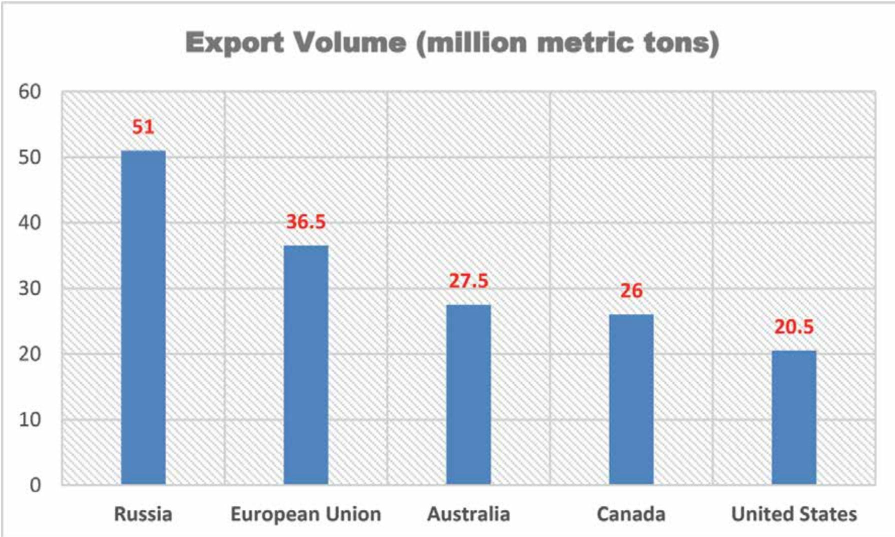
US wheat exports alone were valued at $6.08 billion, with major markets including Mexico, the Philippines, and Japan [76]. The wheat export sector supports employment across the entire supply chain, from farming and processing to logistics and international trade, benefiting both rural and urban economies. Furthermore, wheat exports help maintain favorable trade balances, which are critical for national economic stability. Beyond economic gains, wheat plays a pivotal role in global food security. As an affordable and versatile staple, fluctuations in its prices and supply have far-reaching implications, particularly for developing nations dependent on imports.

In summary, global wheat exports have grown consistently over the past 5 years, with major contributions from Russia, the European Union, and other leading exporters. This growth underscores the importance of wheat in economic development, employment, and food security worldwide, highlighting its critical role in sustaining both global trade and nutrition (**Figure 4**).

### 4.3 Importance of wheat in economy

Wheat holds a pivotal role in India's economy and sustenance, serving as both a key contributor to agricultural GDP and a cornerstone of food security for its vast population. India is the second-largest producer of wheat globally, with production reaching 112.74 million metric tons in the 2022–2023 season [77], according to the Ministry of Agriculture and Farmers Welfare [78, 79]. This extensive production not only meets domestic consumption needs but also bolsters global food supplies, positioning India as a significant player in the international wheat market. In recent years, India has emerged as a notable exporter, with shipments reaching new markets, particularly during disruptions in global supply chains caused by geopolitical tensions, such as the Russia-Ukraine conflict [80]. Wheat exports from India crossed 8.5 million tons in 2021–2022, as per government reports, highlighting its growing importance in stabilizing global food security [81].

The economic importance of wheat is further underscored by its impact on rural livelihoods, nearly 80% of India's farmers are smallholders, and wheat cultivation




| Country | Export Volume (million metric tons) | Percentage Share |
|---|---|---|
| Russia | 51.0 | 31.57% |
| European Union | 36.5 | 22.59% |
| Australia | 27.5 | 17.02% |
| Canada | 26.0 | 16.09% |
| United States | 20.5 | 12.69% |

**Figure 4.**
*Export of wheat in different countries in million metric tons.*

serves as a primary or supplementary source of income for millions of these households [82]. The crop's high adaptability to diverse agro-climatic zones ensures its widespread cultivation, particularly in states like Punjab, Haryana, Uttar Pradesh, and Madhya Pradesh, which are the backbone of India's Green Revolution [83]. It has been found that the wheat's short growth season (90–150 days) allows for a range of cropping techniques, and early-maturing varieties may tolerate terminal drought and heat stress. It is resilient to a variety of soil moisture levels and grows best on clay and loamy soils with sufficient drainage. Its role in crop rotation also helps maintain fertility, improves soil health, decreases soil degradation, breaks pest and disease cycles, and boosts long-term soil sustainability (**Table 2**). The crop is appropriate for rainfed agriculture because of its moderate water-use efficiency. By gaining access to deeper moisture, its deep root systems increase drought resilience and strengthen its resistance to dry circumstances. With improved resilience to climatic stresses like drought, heat, frost, and salinity, it is especially well-suited for low-input farming and marginal soils. Breeding initiatives have greatly increased disease resistance, bolstering the crop's resistance to important diseases like rusts and blights. This, in turn, lowers production losses brought on by pest and disease pressures brought on by climate change. The crop's importance in sustainable agriculture is further supported by the fact that it guarantees steady yields under a variety of circumstances and that climate-resilient cultivars help maintain production even in the face of stress (**Table 2**). A significant portion of the rural population is dependent on wheat for employment, whether directly through farming or indirectly through supply chain activities such as transportation, storage, and processing. Moreover, the Public Distribution System (PDS) heavily relies on wheat as a staple, making it a critical element in government efforts to ensure food security and alleviate poverty.

Research highlights the critical role of wheat in mitigating hunger and supporting nutritional needs in a country where 14% of the population is still undernourished [84]. Wheat-based products contribute to nearly 50% of the caloric intake of an average Indian diet, especially in northern and central regions. Furthermore, the adoption of high-yielding varieties and modern agricultural practices has enhanced productivity, helping to stabilize food prices and contribute to economic resilience. However, challenges such as climate change, water resource constraints, and fluctuating international demand pose risks to the sustainability of wheat production. Recent studies emphasize the need for policy interventions, such as incentivizing climate-resilient farming practices and improving infrastructure, to safeguard wheat's role in the economy and global food systems. In conclusion, wheat's significance extends beyond its economic contributions to embody a lifeline for millions of Indians, both as a source of livelihood and nutrition. With strategic advancements in technology, policy, and global trade relations, wheat can continue to underpin India's agricultural strength while supporting international food security.

In 2023/2024, global wheat utilization is forecast to rise to 789.5 million tons, driven by increased food consumption in Asia and Africa [85], and higher feed use in China. Wheat inventories are expected to remain near record levels at 315 million tons, with a rise in stocks in Ukraine and the United States [86]. Global wheat trade is predicted to decline to *194.4 million tons*, mainly due to reduced imports by the *EU and Türkiye* and smaller exports from *Australia*, *Canada*, and *Ukraine* [87]. However, *Russia* and *Argentina* are expected to increase their exports, with Russia solidifying its position as the world's largest wheat exporter (**Figure 5**).

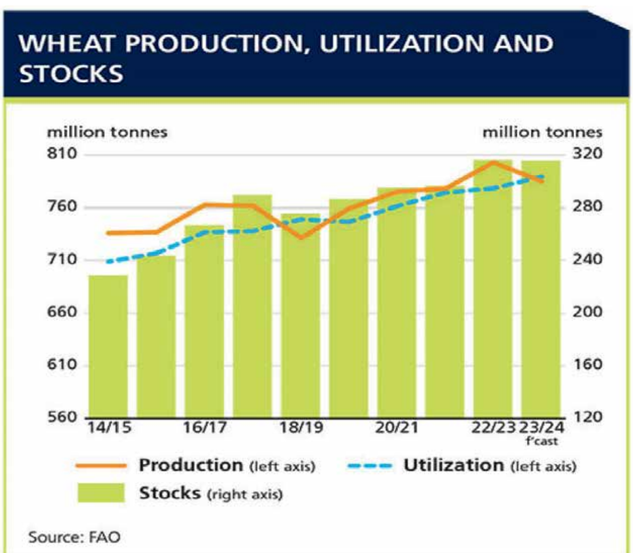



**Figure 5.**
*Wheat production utilization and stocks. https://millermagazine.com/blog/global-wheat-production-fall-in-2023-still-second-highest-ever-5465*

## 4.4 Challenges and opportunities

One of the primary challenges lies in the *declining nutritional quality* of wheat due to intensive farming practices and genetic modifications aimed at increasing yield rather than nutrient density [88]. Modern wheat varieties often exhibit reduced levels of essential micronutrients like *zinc*, *iron*, and *selenium*, leading to widespread micronutrient deficiencies, particularly in developing regions [89]. Additionally, wheat's dependence on synthetic inputs, such as fertilizers and pesticides, has raised environmental concerns while exacerbating soil degradation and loss of biodiversity. Climate change poses further threats, with rising temperatures, droughts, and salinity reducing both yield and grain quality [90]. The prevalence of *gluten intolerance* and celiac disease among certain populations also diminishes wheat's nutritional appeal, creating a need for alternatives or improved wheat varieties [91].

Despite these challenges, wheat offers substantial opportunities to address malnutrition and food security through *biofortification* and sustainable agricultural practices. Biofortified wheat varieties, enhanced with higher levels of *zinc*, *iron*, and *protein*, have already shown promise in combating hidden hunger in vulnerable populations [92]. Advancements in *genomic breeding* and CRISPR technology can further improve wheat's nutritional profile, drought resistance, and resilience to abiotic stresses like heat and salinity [46]. Promoting *whole wheat consumption* rather than refined products can help maximize its dietary fiber, vitamins, and antioxidants, contributing to better gastrointestinal health and reduced risks of chronic diseases such as diabetes and cardiovascular ailments.

Wheat also has the potential to address global food security through *climate-resilient cultivation techniques*, such as precision agriculture, water-efficient irrigation, and crop rotation systems [93]. Strengthening policies that encourage wheat diversification and value addition, such as fortification with micronutrients and the development of gluten-free alternatives, can expand its nutritional accessibility to a broader consumer base. Moreover, wheat-based innovations in *functional foods* and health-promoting products offer opportunities to meet the growing demand for nutritionally enriched and sustainable food solutions. In conclusion, addressing the challenges of declining nutrient content, environmental sustainability, and health-related concerns will require an integrated approach involving *innovative breeding*, *sustainable farming practices*, and *value chain enhancements*. By leveraging these opportunities, wheat can be transformed into a powerful tool to combat malnutrition and shape global food security in an equitable and resilient manner.

## 4.5 Conclusion

Wheat stands as a cornerstone of global food security due to its significant role in nutrition, agriculture, and economic stability. As a dietary staple for over a third of the global population, wheat provides essential macronutrients, micronutrients, and dietary fiber, addressing both caloric needs and micronutrient deficiencies. Its adaptability to diverse agro-climatic regions and agronomic advantages have made it a resilient crop in the face of climate variability, ensuring food supply in vulnerable regions. Furthermore, wheat's contributions to rural livelihoods, international trade, and economic development highlight its broader socioeconomic importance.

However, challenges such as declining nutrient density, climate change, soil degradation, and the rise of dietary concerns like gluten intolerance necessitate a multi-faceted approach to wheat production and consumption. Innovations in biofortification, sustainable cultivation practices, and climate-resilient breeding offer promising solutions to enhance wheat's role in addressing hidden hunger and ensuring global food security. Policies promoting whole grain consumption and reducing post-harvest losses are critical to maximizing wheat's nutritional and economic potential.

In conclusion, through integrated efforts in research, technology, and policy, wheat can continue to serve as a vital crop for nourishing populations and supporting resilient food systems worldwide, even amid evolving challenges.

## 5. Conclusion

In conclusion, wheat is a staple of global food security and a nutritional powerhouse, providing a wealth of macronutrients, micronutrients, and chemicals that promote health. It is essential to millions of livelihoods and national economies because of its extensive cultivation and economic significance. But maintaining its crucial function in the face of environmental difficulties, soil erosion, and new health issues calls for creative solutions. For future generations to have a robust and nourishing supply of wheat, biofortification, climate-resilient crop types, and sustainable agriculture methods are essential. To fully utilize wheat's potential in tackling poverty, malnutrition, and the changing needs of a growing world population, strategic investments and supportive policies will be essential.

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**Chapter 7**

# Adoption of Integrated Pest Management (IPM) for Sustainable Intensification in Wheat

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**Abstract**

Wheat (*Triticum aestivum* L.), the most widely grown cereal, faces rising demand due to population growth and shifting consumption habits. However, its productivity is constrained by numerous abiotic and biotic factors. Among the biotic constraints, insect pests are a major cause of yield loss. This chapter reviewed the insect pests of wheat and their damage and control methods. While chemical pesticides are common, they harm the environment as well as human health. Existing pest management practices among wheat growers lead to economic losses, environmental degradation, and operational inefficiencies that collectively undermine both short-term productivity and long-term sustainability in wheat farming. To address these issues, Integrated Pest Management (IPM) is favored. IPM combines cultural practices, biological control, and host plant resistance for sustainable wheat production. However, adoption of IPM is limited by factors like insufficient farmer knowledge, labor demands, and the complexity of IPM practices. Recent advancements in IPM technologies, including Artificial Intelligence (AI), Geographical Information System (GIS), Global Positioning System (GPS), and machine learning, improve data analysis, optimize pest management, and predict outbreaks. These technologies improve pest control accuracy, promote sustainability, reduce environmental impact, and increase crop yields.

**Keywords:** wheat, integrated pest management (IPM), insect pests, biotic factors, sustainability, biological control

## 1. Introduction

Wheat, a primary food source for 40% of the world's population, is the most widely cultivated cereal globally. Wheat is probably the major crop contributing to global food security, providing about 20% of global dietary energy and protein intake [1]. Since the 1980s, wheat demand has doubled, primarily driven by developing nations, which produce half of the world's wheat. This makes wheat crucial for global food security.

Wheat is economically important, and its price can have a major impact on global food security and stability. For example, when wheat prices rise sharply, riots and revolutions can occur. Global food demand is expected to increase by 35–56% by 2050, and wheat will need to contribute to meeting this demand [2]. Significant yield gains in wheat production over the past 40 years have resulted in a steady balance of supply versus demand. However, predicted global population growth rates and dietary changes mean that substantial yield gains over the next several decades will be needed to meet this escalating demand. Wheat is affected by hundreds of fungal, bacterial, and viral pathogens, which cause diseases of varying severity [3]. A key component to meeting this challenge is better management of fungal-incited diseases, which can be responsible for 15–20% yield losses per annum. Prominent diseases of wheat that currently contribute to these losses include rusts, blotches, and head blight/scab. Other recently emerged or relatively unnoticed diseases, such as wheat blast and spot blotch, respectively, also threaten grain production. Various arthropods pose a significant threat to wheat crops throughout their entire life cycle. These pests, which can be either generalists or specialist feeders, rarely target wheat exclusively. In India, wheat crops face numerous insect pests, including termites, shoot flies, brown wheat mites, armyworms, and aphids [4]. It is estimated that insect pests caused around 5.1% of global wheat yield losses before the Green Revolution. However, these losses increased to 9.3% in the post-Green Revolution era of the 1990s [5]. There are more than 100 species of arthropod pests that attack wheat, most of which are occasional or inhabit limited areas of wheat production, with only a few species of major economic importance [6]. The importance of Integrated Pest Management (IPM) in wheat cultivation cannot be overstated, as it addresses various challenges posed by pests while promoting sustainable agricultural practices. The adoption of IPM in wheat cultivation is vital for enhancing productivity, ensuring economic viability, protecting the environment, and fostering sustainable agricultural practices. By addressing pest management comprehensively, IPM supports both current agricultural needs and future food security challenges. To address environmental, economic, and health concerns, IPM has become the most sought-after method for managing pests. This approach promotes sustainable pest control by reducing the need for harmful pesticides. Although IPM has been successfully implemented in many crops, wheat has only recently become a primary focus [7]. To effectively control insect pests in wheat crops, a deep understanding of their biology, distribution, and the biology of the wheat plant itself is crucial. IPM offers a comprehensive approach that combines various control methods, including cultural practices, biological control, host plant resistance, and chemical treatments. By implementing IPM strategies, we can enhance the efficiency of pest control, minimize input use, and reduce environmental harm. This chapter delves into the key insect pests that threaten wheat crops, examining their life cycles and behaviors, and exploring management techniques to mitigate yield losses. The list of important insect pests infesting wheat crop is given in **Table 1**.

## 2. Details of biology, nature of damage, and management of insect pests of wheat

### 2.1 Armyworm *Mythimna separata* Walker (Lepidoptera: Noctuidae)

Armyworm M. *separata* is present in India, Bangladesh, China, Japan, Australia, and New Zealand [14]. In India, it is distributed in the Indo-Gangetic plains of Punjab, Haryana, Madhya Pradesh, and Uttar Pradesh. The adult moths are thick-bodied and light brown. The caterpillars have three distinct stripes—orange, white,

| Sr. No. | Common name | Scientific name | Family: Order | Pest categories |
|---|---|---|---|---|
| 1 | Armyworm | *Mythimna separata* (Walker) | Noctuidae: (Lepidoptera) | [8] |
| 2 | Wheat Aphids | *Sitobion avenae*, *Sitobion* (*Macrosiphum miscanthi*, *RhopalosiphummaidisandR. Padi* (*Rhopalosiphumrufiabdominalis* (Sasaki) | Aphididae: (Hemiptera) | [9, 10] |
| 3 | Ghujia weevil | *Tanymecusindicus* Faust | Curculionidae: (Coleoptera) | [11] |
| 4 | Termites | *Odontotermes obesus* (Rambur) and *Microtermesobesi* (Holm) | Termitidae: (Isoptera) | [12] |
| 5 | Pink stem borer | *Sesamiainferens* (Walker) | Noctuidae: (Lepidoptera) | [13] |

**Table 1.**
*Major and minor Insect pests affecting wheat crop.*

and brown—running along their sides. They also have a thin, broken stripe down their back. Notably, there are black spots on the top of their four pairs of prolegs. Initially, the larvae are pale white, but they soon turn a vibrant green. These active larvae are constantly moving and spend their days concealed in cocoons. As night falls, they emerge to feed on the leaves [15].

### *2.1.1 Biology and nature of damage*

Adult females are taking between 2 and 5 days to start laying eggs after mating. On average, a female moth lays around 996 eggs. Eggs are laid in cluster form. The incubation period of the egg is 4–5 days [16]. The young caterpillars hatch in 5–7 days. After hatching, they feed on the leaves of the seedlings. Larval development period is 15–23 days [16, 17]. Larva pupates in the soil at depths of 2 cm. However, pupation can occur under dry leaves, stubbles, or fresh tillers. Pupae are yellowish brown and lustrous, with a pupal duration ranging from 8 to 9 and sometimes 10–15 days [17, 18]. The development of one generation takes 25–45 days. Adult is brownish-white in color.

The primary damage to young plants is inflicted by these caterpillars, which target tender leaves in the central whorl; they progressively consume older leaves, completely skeletonizing them. If the infestation is heavy, only the leaf veins remain. Armyworms attack the whole crop in one field and move to another field like an army [15, 19] and also consuming the developing grain heads. This destruction halts further plant growth. While they primarily target spring wheat, winter wheat and spring barley can also be affected.

## **2.2 Wheat aphids (Aphididae: Hemiptera)**

Aphids pose a serious threat to wheat crops, leading to substantial damage. They inflict harm through various methods, such as direct feeding, transmitting plant viruses, and excreting honeydew, which can trigger fungal diseases. Research indicates that aphid damage to wheat varies according to the species and stage of growth [20]. Mainly four aphidsspecies that mainly attack wheat, namely *Sitobionavenae*, *Sitobion* (Macrosiphum) *miscanthi*, *Rhopalosiphum maidis*, and *R. padi* [8]. *Rhopalosiphum rufiabdominalis* (Sasaki) also observed to infesting the roots of wheat [10]. *S. avenae* earlier reported of minor importance, but now it has become severe in the Jammu region. Research indicates that the bird cherry-oat aphid (*Rhopalosiphum padi*) is more damaging to wheat seedlings than the green bug aphid (*Schizaphis graminum*) [21]. During blossoming, greenbug aphids do more damage than bird cherry-oat aphids. *S. avenae* has a wide global distribution, including Europe, Asia, Africa, North and South America. In India, it is found in several states, such as Delhi, Haryana, Himachal Pradesh, Jammu and Kashmir, Madhya Pradesh, Punjab, Rajasthan, Uttar Pradesh, and West Bengal [22]. *M. miscanthi* is also widely distributed across continents like Australia, Asia, and Africa. In India, it is reported from Arunachal Pradesh, Assam, Bihar, Delhi, Himachal Pradesh, Manipur, Meghalaya, Nagaland, Orissa, Punjab, Sikkim, Tamil Nadu, Tripura, Uttar Pradesh, and West Bengal [23, 24].

### *2.2.1 Biology and nature of damage*

#### *2.2.1.1 Wheat aphid (Sitobian avenae)*

The life cycle of aphid *Sitobian avenae* passes through four nymphal instars. The nymphal period ranges from 5 to 7 days. During cold weather, it breeds at a fast rate and reaches the peak of its population in February-March when the ears are ripening. Adults emerge in the form of apterous and alate mates within a day or two after the final molt and start reproducing young ones. The wingless forms produce a significantly higher number of young ones than winged, but their life span is shorter than that of winged aphid. Generally in the field, viviparous apterous forms are common and observed in large numbers [25].

#### *2.2.1.2 Indian grain aphid (Sitobion miscanthi/Macrosiphum miscanthi)*

*Sitobion miscanthi* are apterous, viviparous, and alate females seen feeding on wheat crop. The alate adults appear in the week of January, and by mid-January, apterous form is noticed. Winged female leaves their nymphs scattered all over the plant. The nymphal period is 7–11 days. Aphid gives birth to nymphs varying from one to eight per day. The aphid gives birth to nymphs and varies from 24 to 59, which continues to 11–25 days. During the last one to six days of life, it does not reproduce. The total life is completed within a span of 26 to 39 days. A single aphid gives birth at 1–7 nymphs per day, which continues for 10–32 days; during this period, a female produces 27–53 nymphs. It complete about eight generations between the periods of mid-January to the end of April.

#### *2.2.1.3 Bird cherry-oat aphid (Rhopalosiphum padi)*

The aphid, *Rhopalosiphum padi* passes through four instars. The nymphal development period is about 4 days. Adult longevity of aphid is reported to be 7 days. The total life cycle varied between 11 to 18 days as generation passes on the wheat. The total fecundity per female ranged from 13 to 53 nymphs, and it declined in subsequent generations [26]. The variation in nymphal duration is mostly affected by temperature and humidity. In other case, the nymphal duration varies from 10 to 16 days, and total life span of aphid is reported to be 22–30 days [7]. Aphids, with their piercing-sucking mouthparts, extract phloem sap from plants. When they feed on wheat, they deplete the plant of essential nutrients, hindering growth and yield.

This feeding behavior can also manifest in visible symptoms such as leaf curling, yellowing, stunted growth, and underdeveloped roots [27]. Aphids secrete a sugary substance known as honeydew, which can foster the growth of sooty mold on wheat plants. Sooty mold can impede photosynthesis, leading to reduced plant growth and yield. Research has demonstrated that the severity of sooty mold damage to wheat is correlated with the density of aphid infestations. High aphid populations can significantly amplify sooty mold growth on wheat plants, consequently diminishing plant growth and yield [28]. Honeydew encourages black sooty mold development that leads to 20–80% damage. *R. padi* infested all above-ground plant parts but was more preponderant on leaves and stems (foliage). *Sitobion miscanthi* infested leaves and earheads but were the dominant species on earheads [26].

### 2.3 Termite: *Odontotermisobesus* (Termitidae: Isoptera)

Wheat termites belong to the order (Earlier Isoptera) Blattodea, consisting of 9 families that exists worldwide. The families of termites were further classified as mono-generic families, including Mastotermitidae (holotype *Masotermes darwinensis* in Australia), Indotermitidae (holotype indotermes in India), Stylotermitidae (holotype stylotermes in India), Serrtermitidae (holotype *Serritermes serriferin* Brazil). The family Termitidae comprises 145 Genera and has 4 subfamilies [29] along with near about 3000 described species. Termite fauna of the subcontinent comprised 337 described species and subspecies of 54 genera. Among these, 16 species were found to be damaging to wheat crops in Asia, of which domina species are *Odentotermes obesus* and *Microtermes obesi* [11]. However, *Microtermes obesi* is known to be the most important pest of wheat. The following species of termites attack wheat crops (**Table 2**).

Termites found all over the world except the Antarctic region. Termites distributed to Tropical, subtropical, and temperate regions worldwide. Termite's diversity is found to be very high in the South American region compared to North America and Europe. Out of 3000 known species, termites are extremely abundant in the African region. In Asia, the main distribution is restricted to China, India, Pakistan, Sri Lanka, and Veitnam, totaling 435 species. *Microtermes obesi,* commonly known as Wheat termite, is a very small species of genus *Microtermes obesi* is restricted to wheat habitats of South and Southeast Asian countries, including India, Pakistan, Sri Lanka, Thailand, and Vietnam [34].

#### *2.3.1 Biology and nature of damage*

After the first monsoon showers, winged forms (reproductive castes) leave their colonies for flight to find partners. After fertilization, the queen grows to 11 cm in length and lays over 70,000 kidney-shaped eggs daily. The egg time varies from 30 to 90 days. The majority of nymphs in a colony are workers (sterile caste), accounting

| Sr. No. | Species | Damage (%) | Country | Reference |
|---|---|---|---|---|
| 1 | *C. heimi, O. obesus, O. redemanni, M obesi, O. feae, T. biformis* | 13–100% | India | [29–31] |
| 2 | *O. obesus, M obesi* | 3.10–7.89 | Pakistan | [32, 33] |

**Table 2.**
*List of different species of termites attack on wheat crop.*

for 75–80%. There are 7–8 nymphal instars, and the nymphal duration varies. From 6 to 12 months. They generate primarily laborers and troops. Periodically, they produce fully winged or primary reproductive, which swarm and repeat the cycle. If the primary reproductive die or are removed, some of the larvae may develop into secondary reproductive, which are not fully winged but are still capable of reproduction [35, 36].

The damage starts right from the sowing of the crop until the harvest [37]. Termites destroy the roots, resulting in yellowing of leaves, and ultimately, the injured plant becomes weak and withers away. The affected plants can be easily uprooted with a little pressure from the soil. Strong winds at this stage also bend the spikelet to such an extent that the earheads fall on the ground, resulting in the death of the plant, even before it reaches the harvesting stage. At the earhead stage, the damage is characterized by chaffy earheads with little or no grain formation [38]. Maximum infestation causes at maturity stage as compared to seedling stage except for a few species like *T. biformis*, which inflicts more damage at the seedling stage [30].

### 2.4 Pink stem borer: *Sesamia inferens* (Noctuidae: Lepidoptera)

The pink stem borer has a broad host range that includes wheat, maize, sorghum, ragi, oats, barley, rice, and sugarcane [39–41]. *S. inferens* is extremely polyphagous on different graminaceous plants and diminishes the productivity of cereals and millets. It was accounted from Malaysia, Philippines, Taiwan, China, Japan, Bangladesh, Bhutan, Brunei, Hongkong, India, Indonesia, Korea, Nepal, Pakistan, Singapore, Sri Lanka, Thailand, and Vietnam.

#### *2.4.1 Biology and nature of damage*

Initially, the newly laid eggs of *S. inferens* were small, oval, and had a greenish-creamy white color. As they developed, they gradually darkened, transitioning to a pinkish hue before ultimately turning blackish-gray just prior to hatching. In contrast, unfertilized eggs retained their creamy white color and exhibited a shrunken appearance [42]. The eggs are laid either at the base of plant near the soil level or on the soil surface. These are laid either singly or in clusters [42, 43]. The incubation period varied from 10 to 14 days. The larvae of *S. inferens* are smooth, even-textured, uniformly pinkish-white in color with dark brown to black head, and length of larvae is 30 at full-grown upstage and encompasses six instars in case of millets [44]. Total larval instars are eight [42, 45]. The larval duration lasted for 21–37 days [46]. The obtect pupa is 9 to 14 mm long with a head area of pupa covered with bluish dust, and the remaining body is dark brown [47]. In contrast, pupae of *S. inferens* in sugarcane were robust and brownish, with a tapering abdomen that carried two small “bumps” in the front of the genitalia [43]. They measured 15 to 17 mm in size; females were larger with broad abdomen than males and devoid of any markings making the sex determination easier for the pupa. In wheat, the pupal duration for males is 37 days, and 38 days for females, during the winter season [48]. The adult longevity of male and female ranged from 6 to 7 days and 7–8 days, respectively. The total life span ranged from 63 to 72 days for female and 45–58 days for male, respectively, in the first generation [42].

The neonate pink stem borer larvae remain in groups inside the leaf sheath and feed on the epidermal layer. The original site of its feeding is the bottom-most leaf sheath. Gummy liquid oozes out with water-soaked lacerations appearing outside of the affected leaf sheath due to the early instars feeding and they destroyed 40 and 50 days old plants [42]. The third and fourth instar larvae feed within the stem and produce dead hearts that cause plants to die. In extreme cases, bored midrib concludes with tunneling symptoms on leaf blades, showing ragged manifestation in plants. Seventh and eighth in stars are fed in new tillers; dead hearts are formed, and each tiller has 1–2 larvae in it [42]. Once the stems dehydrated, the larvae left the old tunnels at the earliest and settled in new tunnels [49].

### 2.5 Ghujia weevil: *Tanymecus indicus* (Curculionidae: Coleoptera)

*Tanymecus indicus* Faust (Coleoptera: Curculionidae) is present in India, Myanmar, and Ceylon [50]. It is widely dispersed across India [10]. In India, it is available in Punjab, Bihar, Madhya Pradesh, Uttar Pradesh, Bengal, and Assam. Ghujhia weevil has been identified as a traditional wheat pest in northern India [51]. Barley, gram, peas, lentils, mustard, rice, maize, sorghum, cotton, jute, sunhemp, safflower, indigo, and beetroot are among the crops affected [52, 53].

#### *2.5.1 Biology and nature of damage*

Insect mate frequently and lay 6–76 eggs in 5–11 installments in the soil under clods or in crevices in the ground. The egg period is 6–7 weeks. Young larvae (grubs), after hatching, enter into the soil and eat soil dump. Larval period of weevil is 10–18 days. Larvae pupate in earthen chambers at a depth of 15–60 cm. The pupal stage lasts 7–9 weeks. Adult Weevils are earthen gray and measure about 6.8 mm in length and 2.4 mm in width. Their fore wings are oblong and hind wings are more or less triangular, but they cannot fly. The pest is active from June to December and undergoes larval or pupal diapause during the rest of the year in the soil. The pest has only one generation in a year [36].

Only adults feed on the host plant's leaves and tender shoots. They cut the germinating seedlings at ground level [54]. Often, the crop is resowed. The damage is more severe around October-November when *Rabi* crops are sprouting. The weevils damage seeds sown in the soil, and damaged seeds do not germinate; sometimes, it necessitates resowing [55].

## 3. IPM strategies for wheat

### 3.1 Pest monitoring and surveillance techniques

The next step in IPM is to monitor and identify pests to assess their potential risks and determine appropriate management strategies, including the use of pesticides. Pest surveillance is a cornerstone of IPM, enabling timely intervention decisions based on current pest and natural enemy populations. This is primarily achieved through physical inspection.

Pest monitoring should start immediately after crop establishment and be done on a weekly basis. Within every field, five randomly selected locations, and at each location selected, five plants to record insect counts by following certain procedures (AESA-based IPM Package for Wheat).

### *3.1.1 Insect-specific monitoring process*

To monitor the pest populations on wheat plants, counting and recording both the populations of nymph and adult aphids on the top, middle, and bottom of three leaves per plant should be taken into account. Evaluation of the infestation of the defoliators (e.g., *Helicoverpa*) can be done by determining the percentage of affected plants and counting the number of larvae present per tiller. Effectively monitoring and managing the insect pest complex in wheat crops can be done by deploying 4–5 pheromone traps per acre, ensuring a minimum spacing of 75 feet apart between traps. Replacing the lures every 2–3 weeks and documenting moth catches weekly, particularly for species like *Helicoverpa*. For monitoring the aphid population, set up 4–10 yellow sticky traps per acre, positioned 15 cm above the crop canopy, and for thrips, install an equal number of blue sticky traps at the same height. Record daily counts of aphids and thrips, implementing control measures as needed. Locally available materials, such as empty containers painted yellow and coated with grease or castor oil, can be used to make yellow sticky traps. Additionally, install one light trap per acre at a height of 15 cm above the canopy to monitor and mass-capture insects. Operate the light trap during dusk (6 PM to 10 PM), ensuring an escape route for beneficial insects.

### *3.1.2 Early-season assessments*

Early-season evaluations play a critical role in IPM for wheat, allowing proactive identification and management of pests, diseases, and weeds before they cause substantial damage. Through effective crop monitoring during the early growth stages, the farmer can establish and implement the economic thresholds, thereby reducing the reliance on unnecessary pesticide applications. Advanced technological tools such as drones and remote sensing for early-season assessments further enhance decision-making by providing real-time data on large-scale insights into pest and weed dynamics, thereby supporting more informed decision-making.

### *3.1.3 Regular field scouting*

Scouting and monitoring are vital aspects of effective pest management, enabling farmers to evaluate the level of pests and potential crop damage. Timely scouting, as applied in IPM, facilitates early detection and intervention, preventing significant yield losses. According to [56], effective scouting involves four fundamental practices. For efficient monitoring of wheat crops, collect appropriate background information that includes local weather conditions, soil data, aerial imagery, farm management records, and crop/pest management references. Use appropriate tools such as record sheets, field maps, GPS devices, magnifying glasses, soil probes, sample bags, pliers, cameras, shovels, and coolers to aid in making accurate observations and sample collection. Make routine, systematic monitoring with adequate sampling methods to represent the entire field. Keep scouting activity records, covering pest observations and management actions undertaken and any data relevant to these.

## 3.2 Cultural control measures

Cultural control entails the use of targeted agricultural practices at appropriate times to minimize or prevent pest damage in crops. Some of the IPM strategies that can be used for effective wheat pest management include: Post-harvest removal of crop residues, which can significantly lower pest populations [57]. Timely planting and avoiding late sowing can protect crops from shoofly and armyworm infestations [58]. Eliminating volunteer wheat and alternative hosts, rotating crops, adjusting planting dates, and performing tillage can control pests like wheat curl mite, brown wheat mite, and aphids [59, 60]. Using recommended levels of nitrogen fertilizers can avoid attracting higher populations of armyworms and aphids [61]. Applying well-decomposed farmyard manure can minimize termite infestations. Deep summer plowing at 10-day intervals can reduce pest populations, including juvenile termites, pupae of *H. armigera*, armyworms, and Ghujhia weevils [62]. Destroying crop residues that serve as sources of infestation for termites and shoot flies is crucial. Regular monitoring of pest and defender populations is essential. Installing bird perches (10 per acre) can attract predatory birds, especially for controlling pink borers. Planting barrier crops like maize, sorghum, or millet around wheat fields and guard crops like sorghum or pearl millet can reduce pest numbers, including Helicoverpa (American pod borer) and armyworms. Fish meal traps can be employed for pest monitoring, especially for shoot flies. Early sowing minimizes the risk of aphid attacks, as delayed planting is associated with greater populations of *Coccinellas eptempunctata* and aphid infestations [63, 64].

### 3.3 Biological control methods

Biological control offers a sustainable and environmentally friendly approach to wheat pest management by harnessing the power of nature. To achieve this, IPM may introduce new biocontrol agents into a specific environment or enhance the efficacy of existing natural enemies within a field [65]. This approach involves various strategies, including the conservation and release of natural enemies like parasitoids, predators, and entomopathogenic fungi [59], the utilization of microbial pesticides such as *Bacillus thuringiensis* (Bt) to target-specific insect pests [66], the exploitation of native predators and parasites like Coccinellid beetles, Chrysopa, Syrphid flies, and Cotesia sp., and the employment of entomopathogenic fungi like *Beauveria bassiana* and *Metarhizium anisopliae* to control pests, particularly termites [67]. The larval endoparasitoids *Microplitis mediator* Haliday is described for the first time in the Neotropical Region, parasitizing the wheat armyworm *Mythimna* (*Pseudaletia*) *sequax* Franclemont. Females successfully parasitized the four first instars of the host, with a significant preference for the second and third, in relation to either the first or fourth instars [68]. The following list of biological control agents affect major insect pests of wheat (**Table 3**).

### 3.4 Host plant resistance strategies

Plant resistance to insect pests can arise from morphological, biochemical, or physiological mechanisms. Morphological defenses involve physical barriers like dense trichomes, spines, and tough leaf structures [84]. For example, wheat—(Hessian fly—Pubescence: [85]; Stem sawfly—Solid stem: [86] (**Table 4**).

Physiological defenses rely on biochemical processes, such as the production of secondary metabolites. Integrating resistant wheat varieties into IPM strategies can offer economic benefits to farmers [90]. In aphid–wheat–parasitoid interactions, parasitism tends to be more pronounced in resistant wheat varieties [91, 92]. However, breeding for resistance to arthropod pests often requires balancing this

| Sr. No | Biological control agents | Bioagents | Insect pests attacked | Reference |
|---|---|---|---|---|
| *1* | *Aphidius* spp., *Aphelinus* spp., *Lysiphle bustestaceipes*,*Diaeretiellarapae* | Parasitoid | Aphids | [69–72] |
| *2* | *Trichogrammachilonis*, *Tetrastichus* spp., *Chelonus* spp.. | Egg parasitoids | *H. armigera* and Armyworm | [73–76] |
| *3* | *Bracon* spp., *Ichneumon promissorius*, *Campoletischloridae* | Larval parasitoids | | [77, 78] |
| *4* | *Lissopimpla excels*, *Ichneumon promissorius* | Pupal parasitoids | | [79, 80] |
| *5* | *Apanteles* spp., *Tetrastichus* spp., *Telenomus* spp., *T. chilonis*, *Bracon* spp. | Parasitoids | Pink stem borer | [81, 82] |
| 6 | Coccinellids, syrphids, lacewing, minute pirate bug | Predators | Aphids | [83] |
| 7 | King crow, dragon fly, spider, reduviids, praying mantids, etc. | | *H. armigera*, pink stem borer and army worm | [36] |

**Table 3.**
*List of biological control agents effect on Major insect pest of Wheat.*

| Sr. No. | Insect | Origins of resistance | Reference |
|---|---|---|---|
| 1 | Hessian fly | *Triticum aestivum* accessions Grant, Patterson, 86981RC1–10-3, 8268G1–19-49, KS89WGRC3 (C3), KS89WGRC6 (C6) | [87] |
| 2 | Russian wheat aphid | *Triticum aestivum* genotypes PI 137739, PI 262660, PI 294994, PI 372129, PI 243781 | [88] |
| 3 | Green bug | *Aegilops tauschii* accessions | [89] |

**Table 4.**
*Origins of resistance to key insect pests in wheat.*

trait against other important characteristics, such as yield potential, tolerance to drought, and resistance to diseases [93]. Implementing a comprehensive IPM strategy that incorporates resistant wheat varieties is essential for safeguarding the crop and maximizing yield [94]. Wild relatives resistant to insect pests of wheat are shown in **Table 5**, and about insect biotypes in wheat in **Table 6**.

## 3.5 Chemical control in IPM

### *3.5.1 Role of pesticides in IPM*

The role of pesticides in IPM systems is dependent on various factors, such as crop type, pest species, geographic location, site-specific conditions, weather patterns,

| Sr. No. | Insect pests | Wild species | Reference |
|---|---|---|---|
| 1 | Hessian fly | *Aegilopos tauschii*, *Triticum ventricosum*,*T. turgidum* | [95] |
| 2 | Russian wheat aphid | *T. monococcum*, *T. turgidum* | [96] |

**Table 5.**
*Wild relatives resistant to insect pests of wheat.*

| Crop | Insect | No. of biotypes | Reference |
|---|---|---|---|
| Wheat | Hessian fly *Mayetiola destructor* | 16 | [97] |
| | Aphid *Sitobion avenae* | 6 | [98] |
| | Green bug *Schizaphis graminum* | 7 | [99] |

**Table 6.**
*Insect biotypes in wheat.*

and economic considerations. At present, for many high-value crops, viable and effective non-pesticide alternatives for pest management are still lacking. Even when the populations of pests are controlled using biological or cultural methods, farmers often view pesticides as essential for protecting crops from unexpected pest outbreaks or the potential failure of biologically—oriented IPM strategies.

Pesticides can be strategically used to influence ecological predator-prey relationships within cropping systems and act as a last resort when pest populations exceed established economic thresholds [100]. In numerous agricultural systems, pest populations are closely monitored, with pesticide application occurring only when pest densities surpass the economic threshold. This threshold represents the point at which the anticipated crop loss outweighs the cost of pesticide application [100]. The availability of pesticides capable of halting pest development at critical stages enhances the flexibility of IPM programs. By knowing that pesticides are available as a last resort, farmers are empowered to prioritize biological, cultural, sanitation, and preventive strategies, reducing reliance on chemical control.

### *3.5.2 Judicious use of chemicals*

Chemical control tactics rely on pesticides to manage insect pests shown in **Table 7**. While effective, these methods require careful application to mitigate environmental and human health risks. IPM offers a comprehensive approach that combines cultural, biological, and chemical control strategies to suppress pest populations and reduce pesticide dependency [108]. Insecticide application should be carried out only when pest populations exceed the economic threshold level, taking into account the pest-to-defender ratio.

| Sr. No | Insecticide | Dosage | Insect pests controlled | |
|---|---|---|---|---|
| 1 | Thiamethoxam 30FS | 33 g/kg seed (Seed treatment) | Termites | [101] |
| 2 | Chlorpyrifos 20EC | 3–4 m//kg seed (Seed treatment) | Termites, Pink stem Borer | [102, 103] |
| 3 | Thiamethoxam 25 WG | 20 g/acre | Aphids | [104] |
| 4 | Quinalphos 25 EC | 640 ml/acre | Aphids | [105] |
| 5 | Fipronil 0.3% GR | 20 kg/ha | Pink stem Borer | [106] |
| 6 | Carbofuran 3G | 1000g/ha | Pink stem Borer | [107] |
| 7 | Carbaryl or malathion 5% | @25 kg/ha | Ghujhia weevil | [36] |

**Table 7.**
*List of insecticides recommended for wheat insect pests.*

#### *3.5.3 Economic thresholds for pest management*

An economic threshold marks the point at which insect populations or crop damage reaches a level where the cost of pest control surpasses the value of the lost crop. This threshold can be quantified in various ways, such as insect density per plant or square meter or the extent of leaf damage. The cornerstone of long-term IPM lies in employing preventive measures to maintain insect populations below economically significant levels. Reactive control strategies, such as chemical treatments, should only be implemented when insect infestations pose a direct financial threat to the producer. Accurate identification of pests is crucial for making informed control decisions [109].

#### *3.5.4 Integrated application with biological methods*

IPM for wheat employs a multifaceted approach that leverages biological control agents like predators, parasitoids, and entomopathogens in conjunction with other eco-friendly techniques. This synergistic strategy aims to reduce pest populations and minimize pesticide use. By adopting biological control methods, wheat production can achieve sustainable yields, safeguard the environment, promote biodiversity, and offer cost-effective solutions.

## 4. Case studies and successful implementations of IPM in wheat

Case studies on IPM in wheat are shown in **Table 8**.

## 5. Challenges and limitations of IPM implementation

### 5.1 Economic barriers for farmers

Several economic challenges the widespread adoption of IPM among farmers. A significant initial investment is often needed, especially for small-scale farmers, since conversion to IPM often involves the investment in new technologies, equipment, and training programs. The perceived financial risk associated with IPM can also deter farmers since the long-term benefits of IPM may not be immediately evident, especially when compared to the short-term cost savings of conventional pesticide use. In addition, limited financial incentives can also discourage the adoption of IPM. While IPM offers numerous societal and environmental benefits, farmers may not directly reap immediate financial rewards, particularly from ecosystem services like biodiversity conservation. Subsidies or government support for IPM adoptions are often insufficient to fully offset the costs and risks associated with the transition. Finally, market pressures can discourage farmers from experimenting with innovative methods like IPM. Competitive market dynamics may prioritize low-cost production over sustainable practices, making conventional methods seem more economically advantageous in the short term.

### 5.2 Knowledge gaps and access to information

Limited knowledge about farmers' understanding of pest control hinders the development of effective pest management strategies for smallholder farmers [112].

| Sr. no. | Details | Results | Reference |
|---|---|---|---|
| 1. | **Impact on yield and profitability** | | [110] |
| | Wheat (*Triticum aestivum*) is susceptible to a range of diseases and pests in India, with significant threats posed by, foliar aphids, root aphids, and termites. Integrated Pest Management (IPM) module is designed to address pests such as loose smut, rusts, powdery mildew, termites, and aphids. | **Sowing Stage:**<br>Seed Treatment: For high risk seed-borne diseases- like carboxin, carbendazim @2.5 g/kg seed, or tebuconazole @1.25 g/kg seed before sowing.<br>In areas with a lower risk of seed-borne diseases- Combining *Trichoderma viride* @ 4 g/kg seed with a reduced dose of carboxin.<br>Termite-combination of endosulfan @ 7 ml/kg seed and *Trichodermaviride*.<br>**Seedling stage**- Endosulfan @ 0.8 kg a.i./ha) at first irrigation.<br>**Boot Leaf Stage**: For Karnal bunt, two sprays of *Trichodermaviride*For aphid - Imidacloprid @ 100 ml/hectare.<br>**Earhead Stage**: Infected plants can be identified early and carefully removed and destroyed by burning. | |
| 2 | **Training and education initiatives for farmers** | | [111] |
| | A total of 30 active trainees were selected in the IPM training at KVK, Utukur, Kadapa, during 2015–2016 to 2017–2018. Covered diverse IPM topics, including seed treatment, intercropping, border crops, trap crops, pheromone traps, sticky traps, Neem oil, Bt technology, and economic benefits like increased net income and benefit-cost ratio. | The study found that 85.8% of trainees adopted IPM practices, with 52.8% continuing and 33% discontinuing.<br>Reduced pesticide spraying frequency and promoted safer pesticide handling. | |

**Table 8.**
*Case studies on integrated pest management in wheat.*

While participatory research has enhanced farmers' knowledge of pest control, they often resist adopting labor-intensive IPM strategies [113]. In many developing countries, funding cuts and competition for scarce resources have contributed to a lack of awareness and knowledge about IPM [114]. Given the complexity of IPM, farmer knowledge can be a significant limiting factor [115]. Exposure to technology is crucial for adoption [116], and farmers typically adopt new practices incrementally. Successful adoption requires not only knowledge of the practice itself but also the ability to implement it. Reference [117] argue that IPM advocates have often overlooked the importance of empowering farmers with the skills to use IPM practices, focusing too heavily on the practices themselves.

## 5.3 Environmental considerations

IPM provides several advantages over conventional chemical pest control methods, including enhanced efficacy and environmentally friendly. IPM utilizes a variety of strategies, such as monitoring, prevention, mechanical traps, and natural predators, in the control of pest populations. By minimizing the reliance on chemical pesticides, IPM reduces the danger of environmental contamination and human health hazards.

IPM has a huge environmental benefit in the ways of reduced pesticide use, diminished pest outbreaks, and improvements in soil health. Firstly, by integrating various pest control methods, IPM can significantly reduce the reliance on massive pesticide applications. Secondly, IPM prevents pest outbreaks by using preventive measures such as access control, sanitation, and trapping. Thirdly, this approach promotes soil health via natural and physical methods in the form of mulching, composting, and crop rotation, which reduces the level of harmful chemical fertilizers. In conclusion, from an environmental perspective, IPM helps safeguard soil, water resources, wildlife, beneficial insects, and entire ecosystems [118].

## 6. Future directions and innovations in IPM for wheat

### 6.1 Advances in technology (e.g., precision agriculture)

Precision agriculture is a new modern farming method that involves optimizing agricultural practices using advanced technologies and data analysis. By leveraging Geographic Information Systems (GIS), Global Positioning Systems (GPS), Remote Sensing (RS), and the Internet of Things (IoT), farmers collect real-time data on soil health, moisture levels, pest infestations, and crop performance from various sources, including soil sensors, drones, satellite imagery, and weather stations. This data-driven approach enables informed decision-making, such as targeted irrigation, precise fertilizer application, and timely pest management. As the world faces increasing food demand, resource scarcity, and environmental challenges, precision agriculture offers a sustainable solution to meet global agricultural needs.

### 6.2 Research needs for improving IPM practices

Advances in IPM toward effective, sustainable, and environmentally safe insect pest control require the application of research. Ecological knowledge must be expanded to encompass pest biology, behavior, population dynamics, and the role of natural enemies in maintaining ecological balance. Innovative tools like RS, artificial intelligence (AI), drones, and improved pheromone traps can enhance pest monitoring and early detection. Biological control progress includes investigating new agents, optimizing their utilization, and genetically improving positive organisms to be compatible with other IPM methods. Host plant resistance strategies focus on incorporating pest-resistant traits into crops, understanding pest adaptation, and managing resistance breakdown. Behavioral manipulation techniques, including mating disruption, push-pull strategies, and the use of semiochemicals and plant volatiles, offer additional pest control methods. Pesticide use optimization aims to develop environmentally friendly and target-specific products, integrate biopesticides, and address resistance through novel action modes. Decision support systems, such as predictive models based on ecological and climatic data, alongside real-time digital platforms, can aid in informed IPM decision-making. The impact of climate change on pest behavior, distribution, and outbreaks necessitates adaptive IPM strategies tailored to various scenarios. Socioeconomic research and farmer adoption studies focus on overcoming barriers to IPM implementation, conducting cost-benefit analyses, and providing farmer training programs to enhance knowledge and skills. By prioritizing these research areas, IPM strategies can be refined to become more adaptive, cost-effective, and environmentally sustainable.

### 6.3 Policy recommendations for supporting sustainable intensification

To promote sustainable agriculture and the implementation of IPM, policy recommendations are essential. Investing in comprehensive farmer education programs, such as Farmer Field Schools, empowers farmers with knowledge of IPM principles and their benefits. This enhances their decision-making abilities and resilience to agricultural challenges [119]. Integrating IPM principles into broader agricultural policies, such as the EU's Farm to Fork initiative, is crucial. Setting clear targets for pesticide reduction and sustainability, establishing effective regulatory frameworks for low-risk pest control products, are essential steps toward a more sustainable future [120]. The success of IPM depends not only on scientific and technological advancements but also on supportive policies and international cooperation. Governments worldwide are recognizing the importance of IPM in achieving sustainable agriculture. For instance, the European Union has set ambitious targets to reduce chemical pesticide use by 50% by 2030, stimulating investment in IPM research and implementation [121]. Similarly, the United States Department of Agriculture offers financial incentives to farmers who adopt IPM practices [122].

International cooperation is crucial as pests often transcend national borders. Initiatives like the FAO's Global Action for Fall Armyworm Control exemplify the power of global collaboration in addressing shared pest challenges [123]. As we strive to feed a growing population while protecting our planet, IPM will become increasingly vital. By embracing technological innovations, adapting to climate change, exploring biological solutions, and fostering global cooperation, we can establish a future where sustainable pest management is the standard practice [124, 125].

## 7. Conclusion

Wheat crop, although less susceptible to insect pests compared to other crops, are still vulnerable to a variety of pests that can cause significant damage throughout their growth cycle. The effective pest management requires an integrated approach that considers ecological and social impacts. Farmers can control insect pests sustainably by combining cultural, biological, chemical, physical, and biotechnological control methods. Through ongoing research, developing pest-resistant varieties of wheat, can bring relief in minimizing pest damage and increasing crop yields. To achieve effective implementation of IPM, all agriculture stakeholders, ranging from farmers to policymakers and researchers, extension workers to community leaders, should be well-coordinated and work toward each other. Strong collaborations across sectors result in a sharing of resources, knowledge, and expertise with periodic communication aiming at aligning IPM strategies to the needs in a local situation. The workshops and advisory committees have much to play toward such coordination. Education and training programs are equally important, where farmers and extension agents can be equipped with the required skills to implement IPM and promote its benefits to achieve sustainable agriculture and environmental health. Policy support is also an important driver, where policymakers should develop regulations that encourage the adoption of IPM. Subsidies for non-chemical control methods, financial incentives for farmers, and increased funding for IPM research might be included in such regulations. Monitoring and evaluation are essential elements, consisting of regular observation of pest levels and means of control. Public education campaigns can enhance the demand for IPM through the resultant market demand for sustainably produced crops, thereby motivating the farmers to adopt these methods. Furthermore, technology and research are important to making effective IPM strategies, especially in terms of precision agriculture tools and biological control techniques. Through these combined efforts, stakeholders can ensure that IPM becomes a practical, sustainable solution for modern agriculture. IPM is more than just a pest control strategy; it is a pathway to resilient agricultural systems, healthier communities, and a sustainable planet. In conclusion, the amalgamation of novel technologies with conventional IPM methods is crucial for promoting sustainable wheat production, as it augments pest management efficacy, refines decision-making, and cultivates resilience in agricultural systems, thereby safeguarding food security while preserving the environment for future generations.

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**Chapter 8**

# Toward a Green Capitalism: Balancing Sustainability and Food Security

*Antonioluigi Costato*


## Abstract

The article examines the complex relationship between environmental sustainability and food security, proposing a model of green capitalism inspired by historical challenges and contemporary contexts. Drawing from Jared Diamond, it explores parallelism between the collapse of past civilizations and current environmental risks, exacerbated by climate change and global interconnectedness. Carlo Cipolla's analysis of historical transformations, such as the communal and industrial revolutions, provides a useful framework for mapping paths toward economic sustainability. The Common Agricultural Policy (CAP) 2023–2027 and the European Green Deal emerge as central instruments for integrating sustainability and food security objectives. Decoupled payments and enhanced conditionality reflect a regulatory approach aimed at reducing environmental impact without compromising agricultural productivity. However, challenges such as regulatory complexity and the need for local adaptability arise. The article discusses the role of the CAP in the transition toward resilient agriculture, balancing economic and environmental needs. It advocates for sustainable capitalism grounded in green principles and innovative collaborations, emphasizing the importance of cultural and legislative shifts to achieve a balance between economic growth and planetary preservation.


**Keywords:** decoupling, coupled payments, degrowth economy, CAP 2023–2027, conditionality, sustainability agreements

## 1. Introduction

In recent years, the transition toward a sustainable economy has become a global imperative, driven by the urgency to address escalating environmental crises, mitigate the effects of climate change, and ensure food security in a context of finite resources and a steadily growing global population. In this scenario, the European Union has assumed a leadership role, developing ambitious tools such as the European Green Deal and the Common Agricultural Policy (CAP) 2023–2027, which aims to integrate environmental sustainability with economic productivity. These instruments not only seek to transform agricultural and production systems but also represent an attempt to redefine the fundamental principles of capitalism in a more sustainable direction.

However, the implementation of such models raises complex questions, particularly regarding their potential adaptability on a global scale. Economic and technological inequalities, cultural barriers, political resistance, and the need to tailor strategies to local specificities are just some of the challenges to be addressed. This article explores these issues and offers a reflection on how to construct a "green capitalism" model, drawing on lessons from history and contemporary dynamics.

Building on the contributions of authors such as Jared Diamond and Carlo Cipolla, the analysis examines parallels between the collapse of past civilizations and current threats, aiming to understand how historical mistakes and solutions can guide the development of more resilient strategies. Furthermore, recent European legislative and policy innovations are analyzed, highlighting the potential of the CAP and the Green Deal to strike a balance between food security and environmental sustainability. The recent literature (2022–2024) provides additional insights, delving into topics such as decoupled payments, enhanced conditionality, and eco-schemes, suggesting more flexible and inclusive approaches to managing natural resources and production systems.

Ultimately, this work seeks to outline a path toward a more equitable and sustainable future, where public policies, technological innovations, and cultural transformations converge to ensure the well-being of present and future generations. Achieving this goal requires not only a shift in mindset but also an integrated vision that combines economic growth with respect for planetary boundaries, thereby defining the contours of a new paradigm for global development.

## 2. Lessons from the past for a sustainable future: History, environment, and economy in comparison

### 2.1 Introduction: The link between the past and the present

The environmental challenges the planet faces today are not new in the history of humanity. Although human impact on the environment has reached unprecedented proportions, the issues manifesting today are, in many cases, evolutions of threats that shaped the fate of ancient civilizations. Comparing the past and the present is not merely a historical exercise but an opportunity to understand how past mistakes and solutions can provide valuable lessons for addressing the future.

In this context, Jared Diamond and Carlo Cipolla offer complementary perspectives. Diamond analyzes the environmental causes that led to the collapse of civilizations, while Cipolla identifies the economic and social transformations that have shaped modernity. Both, albeit from different angles, invite us to reflect on how major changes—whether destructive or transformative—affect the relationship between humanity and the environment.

From this historical analysis, insights emerge for building a sustainable future, where the economy and the environment can coexist in balance.

### 2.2 Jared Diamond's analysis: Historical and current environmental hazards

According to Jared Diamond, "the environmental problems we face today are the same eight dangers that threatened societies in the past, with the addition of four others: climate changes caused by human intervention, accumulation of toxic chemicals in the environment, scarcity of energy resources, and depletion of the Earth's photosynthetic capacity."[1]

He argues that, in the past, the causes of the extinction of ancient civilizations were rooted in specific factors: deforestation and habitat destruction, soil issues, water crises, overhunting, introduction of invasive species, population growth, and anthropogenic pressure on the environment.

The author highlights that, in addition to traditional threats, four new dangers have emerged today, directly linked to human activities and global transformations: human-induced climate change,[2] the accumulation of toxic substances in the environment,[3] energy resource shortages, and the depletion of the Earth's photosynthetic capacity.

Diamond urges us to reflect on the fact that we are facing challenges similar to those that led to the collapse of past societies but, on a much larger scale, exacerbated by global interconnectedness. Humanity has the responsibility to choose between two paths: adopting a sustainable approach based on reducing environmental impact and fostering global cooperation[4] or continuing along the path of unsustainability, risking a collapse that, this time, could involve the entire planet.[5]

A concrete example that demonstrates how historical environmental problems remain relevant, often as the root of modern ones, is deforestation (**Figure 1**).[6]

### 2.3 Carlo Cipolla: Historical transformations

With this brief anthropological premise, it is possible to outline another historical-social reflection based on the thought of Carlo Cipolla, one of the greatest historians of the Italian economy. In one of his essays, Cipolla identifies three fundamental

[1] Ref. [1]. The book explores the causes that led to the decline and disappearance of various societies throughout history, highlighting environmental factors and their interactions with social, economic, and political dynamics. The quoted statement summarizes one of the central themes of the book: the environmental problems faced by past societies remain relevant today but are now compounded by new dangers stemming from human activities on a global scale.
The massive use of fossil fuels, deforestation, and other activities have accelerated global warming, triggering extreme weather events, glacier melting, rising sea levels, and desertification.

[2] The massive use of fossil fuels, deforestation, and other activities have accelerated global warming, causing extreme weather events, glacier melting, sea level rise, and desertification.

[3] The spread of substances such as pesticides, heavy metals, and plastics has contaminated ecosystems, food chains, and vital resources, with negative impacts on biodiversity and human health.

[4] The reliance on non-renewable energy sources (coal, oil, natural gas) has led to a global energy crisis, driving the pursuit of solutions that are not always sustainable or equitably distributed.

[5] The degradation of forests, grasslands, and agricultural areas has reduced the planet's capacity to absorb $CO_2$ and produce oxygen, threatening the life cycle of ecosystems.

[6] The Rapa Nui civilization on Easter Island suffered a collapse largely caused by uncontrolled deforestation. The inhabitants cut down almost all the trees to build canoes, transport statues, and obtain timber. This led to soil erosion, loss of biodiversity, and shortages of essential resources for survival, such as food and wood. The destruction of the natural habitat directly contributed to the population's decline and the collapse of the society. For further details, see. Ref. [2].

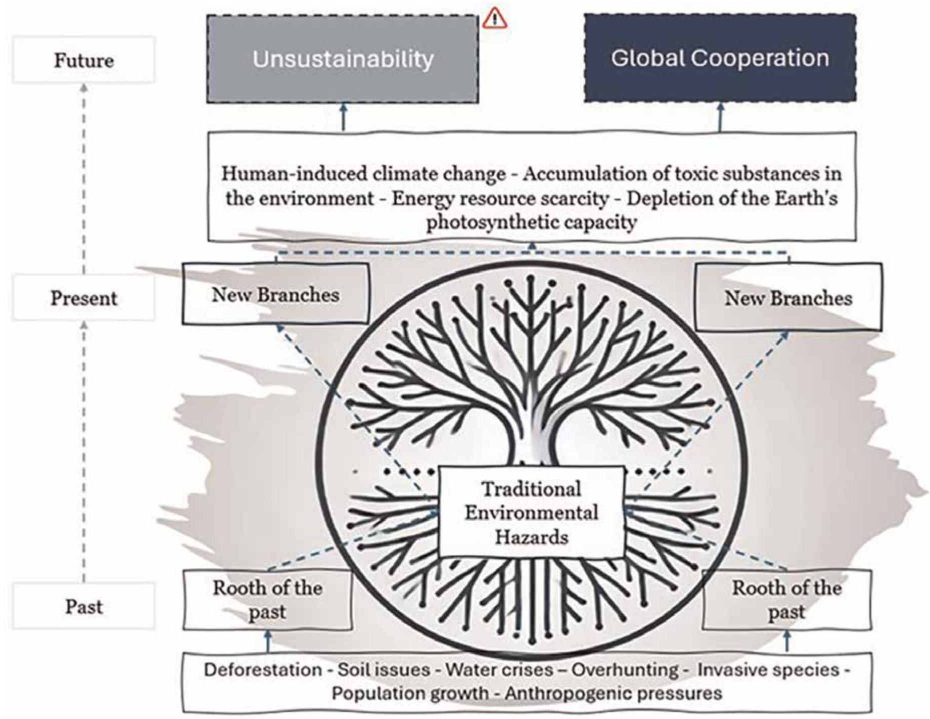


**Figure 1.**
*Jared Diamond's analysis: Historical and current environmental hazards.*

transformations that marked the development of Western Europe between the tenth and ninteenth centuries[7]:

The Communal Revolution (tenth–thirteenth centuries): With the emergence and establishment of communes, especially in Italy, new forms of political and economic organization were introduced, fostering urban and commercial development.

The Scientific Revolution (sixteenth–seventeenth centuries): Marked by a profound transformation in thought and knowledge, the scientific method emerged, and discoveries were made that revolutionized the worldview and technology.

The Industrial Revolution (eighteenth century): Introduced the widespread use of machines and new technologies in production, radically transforming the economy, society, and labor structures.[8]

Following a thread similar to that outlined by Diamond, these three historical revolutions can be correlated to the transitions necessary for building a contemporary sustainable economy:

[7] The dynamics of the three revolutions identified by Carlo Cipolla (the communal revolution, the scientific revolution, and the industrial revolution) are not exclusive to Italy but have broad applicability to the rest of Europe, albeit with some differences due to the historical, political, and cultural specificities of various countries Ref. [3].

[8] Cipolla analyzes how these three revolutions interacted and contributed to positioning Europe at the center of global economic, technological, and cultural development.

- The communal revolution can be compared to local governance in sustainability.[9]
- The scientific revolution connects to technological innovation for addressing environmental challenges.[10]
- The industrial revolution can be linked to the necessary transformation of production chains toward circular, low-emission models[11] (**Figure 2**).

### 2.4 Historical lessons and the role of agriculture

The reason this work begins by highlighting analogies between the past and the present is to emphasize that fundamental lessons can be drawn from history.

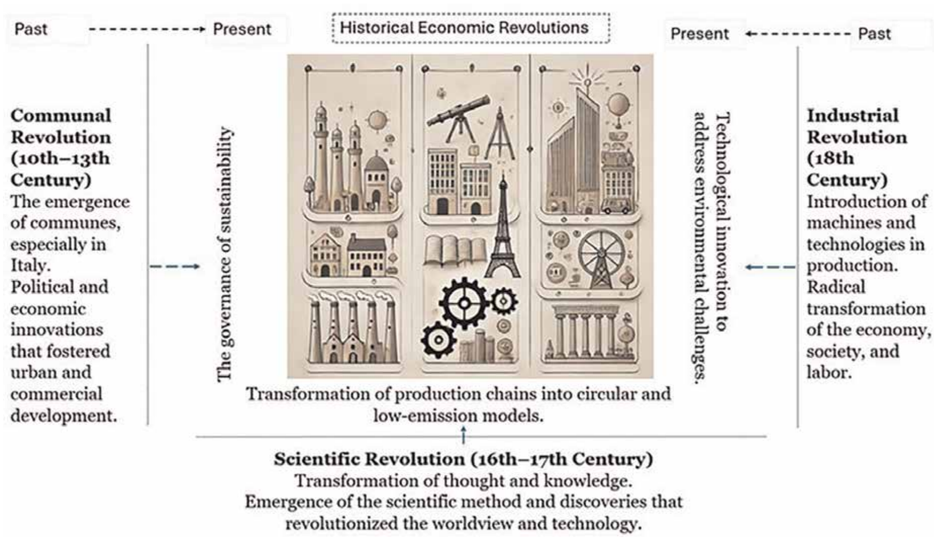


**Figure 2.**
*Carlo Cipolla historical transformations and the present.*

[9] Today, the principles of local governance are fundamental to sustainability policies, such as smart cities and local climate initiatives. Local communities play a crucial role in the sustainable management of resources, promoting circular economy, regenerative agriculture, and resilient urban planning. The collective and participatory responsibility developed during the communal revolution underpins many bottom-up governance initiatives in the environmental field.

[10] The transition to a sustainable economy requires scientific and technological innovations to reduce $CO_2$ emissions, improve energy efficiency, and create eco-friendly alternatives. Technologies such as artificial intelligence, big data, and renewable energy represent the legacy of a rational and methodical approach introduced during the scientific revolution. Today, science is also called upon to unite interdisciplinary expertise, much like the scientific revolution brought together mathematics, physics, and astronomy.

[11] The current challenge is to transform the traditional industrial model into a sustainable industrial system based on renewable energy, waste reduction, and decarbonized production. The Industrial Revolution taught us that economic progress is tied to technological innovation; however, today, this progress must also encompass social and environmental responsibility.
Models such as Industry 4.0 or the green economy reflect an evolution of the industrial paradigm toward sustainability.

As Cicero wrote: "Historia vero testis temporum, lux veritatis, vita memoriae, magistra vitae, nuntia vetustatis."[12]

Building on these premises, we will analyze the economic and legal scenarios related to agriculture, focusing on coupled[13] and decoupled[14] production subsidies in Italy and Europe. Additionally, we will examine the relationship between agricultural production aimed at food security and that oriented toward environmental sustainability.

In the case of humans, a species not subject to predation, the sustainability of its evolution has been influenced by the use and abuse of industrial technologies and the intensive exploitation of natural resources. The critical question is how to reconcile sustainable[15] development while simultaneously ensuring certain quantitative standards.

There is no universal formula for implementing green growth strategies. The transition to a greener economy depends on the policies adopted, the institutional framework, the level of development, resource endowments, and specific environmental challenges. Advanced, emerging, and developing countries face different challenges and can seize distinct opportunities; the same applies to countries with diverse economies and political circumstances.

## 2.5 The society of growth and degrowth

According to a renowned author,[16] it is necessary to abandon the model of a society based solely on growth—a society consumed by an economy whose sole objective is growth for the sake of growth. This logic does not aim to increase production to meet needs but rather to perpetuate infinite growth, justified by the idea of limitless consumption, leading to consequences such as the senseless increase of waste and pollution.[17] Essentially, it is a model that leads to the destruction of the planet [4].

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[12] Translated: "History is the witness of the times, the light of truth, the life of memory, the teacher of life, the messenger of antiquity." This quotation is found in *De Oratore*, Libro II, Sezione IX, Utet, Milano, 1977, pg. 225. Cicero emphasizes how history provides valuable lessons, serving as a guide for the present and the future.

[13] Coupled support in agriculture is a form of financial assistance provided to farmers that is directly linked to the production of specific crops or livestock. This type of aid aims to encourage the production of certain agricultural products deemed strategic for economic, social, or environmental reasons.

[14] Decoupled support, on the other hand, is not dependent on the production of specific goods. Farmers receive assistance based, for example, on the area of land cultivated or the adoption of sustainable practices, regardless of what they grow or raise. Decoupled support is considered less market-distorting compared to coupled support - The basic payment, greening payment, young farmers payment, and small farmers payment are defined as "decoupled" since the support is provided independently of production.

[15] Sustainable development is defined as development that provides ecological, social, and economic opportunities to all members of a community without posing a threat to the vitality of the natural, urban, and social systems on which these opportunities depend.

[16] Marco Buonaiuti is an Italian economist and professor, born in 1962, known for his studies in bioeconomics and degrowth. He has taught at the Universities of Modena and Bologna and is currently a professor at the University of Turin.

[17] Mauro Bonaiuti proposes a model of society that prioritizes human and environmental well-being, in contrast to the dominant paradigm of unlimited economic growth.

For scholars advocating[18] for a degrowth society, the main points of contention with the so-called unlimited growth society (or growth at all costs) are as follows:

- GDP problem: These authors criticize the idea that Gross Domestic Product (GDP) is an indicator of well-being, arguing that it fails to account for environmental and social damages.
- Planetary limits: They highlight how an economy based on unlimited growth is incompatible with the planet's finite resources and contributes to ecological and climate crises.
- Degrowth is not recession: Degrowth is not a forced economic contraction but a radical rethinking of economic and social priorities (**Table 1**).

### 2.6 Common agricultural policy and European green deal

In this context, the European Union's 2023–2027 Common Agricultural Policy (CAP) introduces reforms that can be linked to the principles of the degrowth society. The latter emphasizes environmental sustainability, reduced consumption, and the promotion of local economies. The decoupled payments of the CAP and the principles of the degrowth society can be connected by analyzing how these tools influence agricultural models and sustainability.

Decoupled payments, introduced with the 2003 Fischler reform[19] and consolidated in subsequent reforms, aim to support farmers' incomes without linking them to production levels, thereby separating public support from agricultural output. The CAP reforms in the twenty-first century have significantly reduced the EU's intervention in markets, shifting the focus from production-oriented support—such as coupled payments—to environmental goals.

This trend has led the CAP to formulate a series of programs aimed at sustainability, such as greening and biodiversity promotion, giving member states considerable discretion in implementing the most relevant initiatives.[20]

The communication of November 11, 2019, known as the European Green Deal, aims to lead Europe to "climate neutrality[21]" by 2050. This program, combined with the need to preserve and promote biodiversity, represents an almost complete reversal in the way agriculture is conceived. From its origins to the present day, agriculture has

[18] Among which we remember, in addition to Refs. [5–7].

[19] The Fischler Reform, introduced in 2003 and promoted by Franz Fischler, then European Commissioner for Agriculture, represents one of the most significant transformations in the history of the European Union's Common Agricultural Policy (CAP). The central objective of the reform was to make European agriculture more market-oriented, environmentally sustainable, and consistent with the rules of the World Trade Organization (WTO). The main regulation enacting this reform was Council Regulation (EC) No. 1782/2003, adopted on September 29, 2003.

[20] An overview of the evolution of the CAP can be found in Ref. [8].

[21] Neutralità climatica, infatti, significa raggiungere le "zero emissioni nette", ovvero un completo A balance between the amount of greenhouse gas emissions we will still produce and those we can absorb from the atmosphere, for example, through forest growth or specific technological solutions.

| Topic | Detail | Source |
|---|---|---|
| Environmental and Economic Impact of Unlimited Growth | Between 1970 and 2020, the global material footprint tripled (from 27 billion to over 100 billion tons annually), while the world population only doubled. This highlights the disproportionate growth in resource consumption compared to demographic growth. | UNEP |
| Global Material Footprint | Global annual waste production is expected to increase from 201 billion tons in 2016 to 3.4 billion tons by 2050, with developed countries as the main contributors. | World Bank |
| Waste Production | Between 1990 and 2020, global $CO_2$ emissions increased by 6.0%, rising from 22 billion to over 36 billion tons annually. | Global Carbon Project |
| Carbon Emissions<br>Planetary Limits | This is attributed to economic models focused on unlimited growth with little regard for environmental limits. | |
| | The Global Footprint Network indicates that humanity currently consumes resources equivalent to 17 Earths annually. | Global Footprint Network |
| Use of Planetary Resources | The 2023 Earth Overshoot Day was on August 2, with significant variations in industrialized countries (e.g., in Italy, it occurs as early as May). | |
| Biodiversity Loss<br>Critique of GDP as a Measure of Well-being | Over the past 50 years, the WWF's Living Planet Index reports an average decline of 69% in global vertebrate populations, primarily due to activities linked to economic growth, such as deforestation and urbanization. | WWF |
| In equality and GDP | Between 1980 and 2020, the income of the richest 1% of the global population grew almost twice as fast as that of the poorest 50%. This shows that GDP growth does not always translate into equitable wealth distribution. | World Inequality Network 2022 |
| Cost of Environmental Damage<br>Benefits of Degrowth | Unaccounted environmental damage, such as pollution and climate change, costs the global economy over $300 billion annually. | UNEP |
| Reduction of Emissions | Studies show that degrowth-oriented economic models could reduce global carbon emissions by up to 50% by 2050 while maintaining comparable levels of well-being. | Post-Growth Institute |
| Reduced Working Hours | Countries with reduced workweek policies, such as Denmark and the Netherlands, show that fewer weekly hours can improve well-being and reduce the ecological footprint without compromising quality of life. | N/A |

**Table 1.**
*Some metrics for a degrowth economy*

contributed to massive deforestation, removing tree species that capture and store large amounts of $CO_2$ and selecting more productive plant and animal species while discarding or eliminating other varieties [9].

The agri-food system, as a whole, is an ideal field for applying the Sustainable Development Goals (SDGs) outlined in the 2030 Agenda. In this context, the European Union plays a leading role, setting new sustainability targets integrated into the European strategic framework and the priorities of the European Commission [10].

In the European Commission's communication *"The Sustainable Future of Europe: Next Steps. European Action for Sustainability"* of November 22, 2016, it is reiterated that "sustainable development has long been at the heart of the European agenda." This underscores how sustainability is a deeply rooted theme in the EU's strategy, now more critical than ever for addressing contemporary global challenges.

The application of the European Green Deal to the rest of the world, on the other hand, presents significant opportunities but also complex challenges. On one side, the Green Deal can serve as a model to promote a global ecological transition, encouraging decarbonization, sustainable agriculture, circular economy practices, and biodiversity protection. However, its implementation on a global scale faces obstacles related to economic, technological, and political inequalities among countries. While developed nations can sustain substantial investments in clean energy and innovation, many developing countries are still struggling to meet basic needs, making it challenging for them to adopt high environmental standards.

Moreover, the lack of a uniform international regulatory framework and the risk of "carbon leakage" further complicate the dissemination of these policies.[22] To address such issues, it is crucial to develop mechanisms for international cooperation, such as climate financing, technology transfer, and capacity-building programs, to ensure that the green transition is fair and inclusive on a global scale (**Figure 3**).[23]

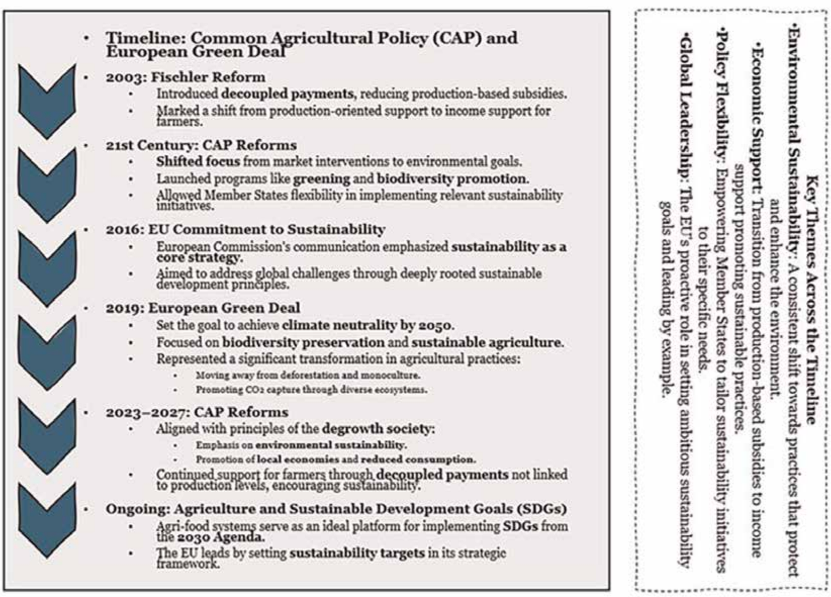


**Figure 3.**
*Timeline: Common agricultural policy (CAP) and European green deal and the key themes across the timeline.*

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22 *Green Transition*, https://reform-support.ec.europa.eu/what-we-do/green-transition_it?utm.

23 *Climate financing, the Council adopts conclusions ahead of COP 27,* https://www.consilium.europa.eu/it/press/press-releases/2022/10/04/climate-finance-council-adopted-conclusions-ahead-of-cop27/?utm.

## 2.7 Some policy recommendations

### *2.7.1 Strengthen the link between the CAP and the green deal for an inclusive ecological transition*

It is recommended to consolidate the principles of the European Green Deal within CAP policies by further encouraging regenerative agricultural practices and biodiversity conservation. This can be achieved through targeted funding mechanisms, such as incentives for organic farming and agroforestry systems, and awareness campaigns to guide consumer choices toward sustainable products.

### *2.7.2 Promote international cooperation for global sustainable agriculture*

The European Union should intensify efforts to transfer green technologies and foster partnerships with developing countries. Establishing an international regulatory framework that includes financial incentives and tools for emissions management could ensure a fair green transition, overcoming the risk of "carbon leakage" and addressing global economic disparities.

### *2.7.3 Support the resilience of local economies to reduce dependence on imports*

Policies aimed at strengthening local agricultural economies should be implemented, promoting short supply chains and encouraging food self-sufficiency. This approach contributes to decarbonization, reduces risks related to global crises, and enhances the cultural and environmental heritage of rural European regions (**Figure 4**).


**Figure 4.**
*Some political reccomendations.*

### 2.8 Conclusion: Sustainability as a necessary balance

The comparison between today's environmental challenges and those faced by past civilizations highlights the need to learn from historical dynamics to avoid repeating mistakes that could lead to a global collapse. Jared Diamond's reflections emphasize that environmental problems are often evolutions of ancient threats, now amplified by a globally interconnected and technologically advanced context. Similarly, Carlo Cipolla's perspective invites us to consider how major historical transformations, such as the communal, scientific, and industrial revolutions, can offer useful analogies for shaping a more sustainable contemporary development model.

Sustainability emerges as the cornerstone of a possible balance between economy and environment—a choice humanity must pursue through innovative and collaborative approaches. The Common Agricultural Policy (CAP) and the European Green Deal represent concrete steps toward more environmentally friendly agriculture, aligning with the principles of degrowth, which opposes the paradigm of unlimited growth. However, to ensure an effective transition, it is crucial that European policies are accompanied by a cultural and social shift that prioritizes waste reduction, the promotion of local economies, and the protection of biodiversity.

Ultimately, history teaches us that change is inevitable, but its direction depends on collective choices. A sustainable development model requires not only technological innovations but also a profound shift in mindset, one capable of integrating lessons from the past with the needs of the present and the opportunities of the future. This path, though complex, represents the only way to reconcile human well-being with the respect for planetary boundaries.

## 3. The CAP 2023–2027: A balance between food security and environmental sustainability

### 3.1 Introduction: Complexity and contradictions of the CAP 2023–2027

Today's legislator operates in an extremely complex and contradictory context. On the one hand, they are tasked with protecting agricultural production to ensure food security, particularly in light of unforeseen and significant events, the so-called black swans[24] (e.g., the COVID-19 pandemic and ongoing conflicts). On the other hand, they must address the numerous challenges associated with environmental protection in the face of profound climate changes, which many argue, are closely linked to humanity's impact on the planet.

### 3.2 The European green deal and the agricultural sector

In this context, the European Union has adopted a series of strategies, including the European Green Deal, aimed at redefining the production and consumption model by promoting sustainability across all economic sectors. The agricultural sector, in particular, plays a crucial role in this transformation, both for its contribution to reducing greenhouse gas emissions and its potential for sustainable land management.

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[24] A black swan is an exceptionally rare event that often results in highly negative consequences. These are events that cannot be predicted in advance but, in hindsight, may appear obvious.

The Common Agricultural Policy (CAP) 2023–2027 serves as a key tool for addressing these challenges by integrating objectives related to food security, environmental protection, and strengthening the socioeconomic fabric of rural areas.

Within the strategic framework of the European Green Deal are the communications from the European Commission and the European Parliament to the Council on May 20, 2020, which introduce important strategies for the agricultural sector. These include initiatives such as *"From Farm to Fork: for a Fair, Healthy and Environmentally-Friendly Food System"* and *"Biodiversity Strategy for 2030: Bringing Nature Back into Our Lives."*[25] The ambitious goals of these strategies aim to enhance environmental sustainability across all productive sectors while intensifying efforts to combat climate change.

In this perspective, the agricultural sector is also deeply involved, as it is simultaneously a risk factor for greenhouse gas emissions and a vital resource for land conservation, preventing depopulation of rural areas, and mitigating hydrogeological risks [11].

### 3.3 The CAP 2023–2027: Legislation and subsidiarity

The proposals for the CAP 2023–2027 date back to a period prior to the adoption of the Green Deal, yet they address similar issues, particularly the complex relationship between agriculture and environmental[26] protection. The new European legislation is structured around three main regulations:

- Regulation (EU) 2021/2015, which sets out rules on support for the strategic plans that Member States must draft under the CAP, financed by the EAFRD (European Agricultural Fund for Rural Development) and the EAGF (European Agricultural Guarantee Fund)[27];

- Regulation (EU) 2021/2116, concerning the financing, management, and monitoring of the CAP[28];

- Regulation (EU) 2021/2117, which amends, among other things, the regulation on CMOs (Common Market Organizations) (Regulation 1308/2013) and the regulation on quality products (Regulation 1151/2012)

In compliance with the principle of subsidiarity, the CAP delegates the development of national strategic plans to member states, which establish the framework for

[25] See, respectively, documents COM (2020) 381 and 380 of May 20, 2020.

[26] As highlighted in the European Court of Auditors' Special Report 16/2021 *Common Agricultural Policy and Climate*, the impact of the 2014–2020 CAP on combating climate change has been, despite its intentions, modest.

[27] This regulation repeals, as of January 1, 2023, Regulations No. 1305/2013 and 1307/2013, concerning rural development and direct payments, respectively. It consolidates the previous frameworks established by Regulation 1305/2013 (on direct payments) and Regulation 1307/2013 (on rural development measures) and includes provisions on conditionality.

[28] Which repeals Regulation 1306/2013 as of January 1, 2023.

measures to be implemented at the national level.[29] Specifically, the principle of horizontal[30] subsidiarity promotes the direct involvement of citizens, associations, and local communities in managing public functions, ensuring that decision-making power is exercised as closely as possible to the citizens [12].

In the current legal framework of the European Union, subsidiarity has taken on a central role in defining competences and the functioning of the EU's multi-level governance system.[31] The future prospects for the principle of subsidiarity, which regulates the relationship between state systems and the EU, include strengthening democratic participation, enhancing social cohesion, and monitoring and adapting the regulatory framework to ensure its uniform and effective application.

In this context, subsidiarity[32] proves to be a fundamental principle for addressing the EU's current challenges, such as the environmental crisis and ecological transition,[33] crisis management,[34] social policy and welfare,[35] agricultural policy and territorial cohesion,[36] as well as digitalization and participatory governance[37].

### 3.4 Objectives of CAP 2021/2015

Article 5 of Regulation (EU) 2021/2015 identifies three general objectives:

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[29] On the one hand, the Institutions, primarily the Commission, relieve themselves of the actual implementation of the Common Agricultural Policy by "offloading" it onto the Member States. On the other hand, the Member States, now bearing greater responsibility for managing the CAP, will no longer be able to shift the discontent of stakeholders regarding the burdensome commitments and complexity of the system onto the European Institutions.

[30] Horizontal subsidiarity is a legal and political principle concerning the relationship between public institutions and private entities, such as citizens, associations, businesses, and local communities. It is based on the idea that power and responsibility should be entrusted to the levels closest to the citizens and that public institutions should intervene only when private entities are unable to perform certain tasks or pursue specific objectives.

[31] Legal References: Charter of Fundamental Rights of the EU (Art. 1 and Art. 41): Promotes the dignity and active participation of citizens in public decision-making. EU Treaties: Emphasize the participatory approach and public-private partnership, particularly in the contexts of economic, social, and territorial cohesion.

[32] Per un approfondimento si legga, Refs. [13, 14].

[33] Subsidiarity allows Member States and regions to develop local environmental policies in line with the European Green Deal, while assigning the EU the role of coordinating large-scale actions, such as the carbon market or emissions regulation.

[34] During the COVID-19 pandemic, subsidiarity balanced the EU's competencies in managing health emergencies with national responsibilities, highlighting the need for joint action in areas such as research, vaccine distribution, and economic coordination.

[35] Horizontal subsidiarity promotes the involvement of local authorities, associations, and private entities in providing social services and supporting vulnerable groups in the population, in line with the European Pillar of Social Rights.

[36] Through the Common Agricultural Policy (CAP), the principle of enhanced subsidiarity allows Member States to develop national strategic plans while respecting the common European objectives of sustainability and food security.

[37] Subsidiarity guides digital transformation strategies, ensuring that local communities have a voice in decisions concerning infrastructure, access to digital services, and data protection.

1. Promote a competitive, resilient, and smart agricultural sector capable of ensuring long-term food security.

2. Support and strengthen environmental protection, including biodiversity and climate action.

3. Strengthen the socioeconomic fabric of rural areas.[38]

From an analytical perspective, point (a), focused on food security, may appear partially in conflict with point (b). For example, some environmental protection measures, such as reducing emissions from agricultural machinery or more moderate use of herbicides and pesticides, could decrease crop productivity, favoring environmental sustainability objectives.[39] Conversely, points (a) and (c) can be considered complementary, reflecting the long-standing debate between productivity and social development.[40]

### 3.5 CAP interventions and conditionality

Title III of the regulation represents the most relevant section. It governs:

- Direct payments, both decoupled and coupled (Articles 16–41);

- Interventions for certain specific products (Articles 42–68);

- Second-pillar interventions (Articles 69–84).

Among the provisions common to all types of intervention, those regulating conditionality stand out. This principle establishes that, to access the system of EU payments, farmers must comply with rules related to proper agronomic management of land, environmental protection, public health, and animal welfare, with penalties applied in cases of non-compliance.[41]

Conditionality, in effect since 2005, is a cornerstone of the Common Agricultural Policy (CAP), making most payments contingent on adherence to regulations concerning the environment, health, and animal welfare. However, it has complex

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[38] https://eur-lex.europa.eu/legal-content/IT/TXT/PDF/?uri=CELEX:32021R2115.

[39] Globally, agriculture accounts for approximately 22% of greenhouse gas emissions, with a lower share in Europe and Italy (9 and 7%, respectively). However, the sector is also a significant contributor to biodiversity loss, such as the decline of pollinating insects.

[40] The relationship between cities and the countryside throughout history has been marked by continuous interdependence and tension. In ancient and medieval societies, the countryside was the productive heart, providing food and resources to cities, which in turn served as administrative, religious, and commercial centers. During the Industrial Revolution, the city became a symbol of progress and innovation, attracting rural populations in search of opportunities, often at the expense of the countryside. In the twentieth century, massive urbanization accentuated this dichotomy, but recent environmental crises have led to renewed interest in a sustainable balance between cities and the countryside, highlighting rural areas as guardians of biodiversity and cultural traditions.

[41] This mechanism was transferred from Regulation 1306/2013 to the Strategic Plans Regulation No. 2021/2115, reaffirming its objectives related to environmental protection, plant health, and animal welfare.

aspects and certain contradictions in terms of effectiveness, as highlighted by the European Court of Auditors:

- The objectives and scope of conditionality are not clearly defined, making its intended purpose unclear.
- The regulatory framework is overly complex.
- Conditionality and rural development are not well-coordinated.

Member States have not implemented sufficiently effective control and sanction systems.[42]

As a result, the control system provides insufficient guarantees of farmers' compliance with obligations. Furthermore, the data on controls and infractions provided by member states are often unreliable, while monitoring by the Commission is inadequate.[43]

### 3.6 Enhanced conditionality and eco-schemes

In Regulation 2021/2115, "conditionality" has been reformulated as "enhanced conditionality."[44] This incorporates rules for maintaining land in good condition as well as commitments that, under the previous Regulation 1307/2013, were included in greening.[45] Additionally, the regulation places greater emphasis on environmental aspects by introducing the so-called eco-schemes: a set of commitments required to obtain a specific payment related to climate, environment, and animal welfare.[46]

The introduction of enhanced conditionality and the so-called eco-schemes highlights the growing importance attributed to environmental sustainability in the agricultural sector. However, a prominent economist argued in an essay [15] published a few years ago that conditionality measures do not account for the specificities of individual countries and may undermine long-term economic growth. He advocates

[42] Special Report n. 8/2008, https://www.eca.europa.eu/lists/ecadocuments/sr08_08/sr08_08_it.pdf.
[43] This provision was incorporated from Regulation 1306/2013 into the Strategic Plans Regulation No. 2021/2115, reaffirming its objectives related to environmental protection, plant health, and animal welfare.
[44] Enhanced conditionality: CAP payments to beneficiaries are linked to a stricter set of mandatory requirements. For example, at least 3% of arable land on each farm must be allocated to biodiversity and non-productive elements, with the possibility of receiving support through eco-schemes to reach 7%. Wetlands and peatlands are also protected.
[45] Article 43 of Regulation 1307/2013 included three measures: (a) Crop diversification, meaning the simultaneous presence of different crops (this measure primarily aimed at soil protection), provided that more than 10 hectares were dedicated to arable land; (b) Maintenance of permanent grassland (a measure aimed at promoting carbon sequestration); (c) Establishment of areas of ecological interest (AEIs) for farms with at least 15 hectares of arable land (a measure for biodiversity protection).
The greening measures were mandatory and were additional to those of conditionality.
https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ: L:2013: 347:0608:0670:IT:PDF.
[46] L. COSTATO, L. RUSSO, *op. cit.*, pg. 142 ss.

for a more flexible approach that is sensitive to local needs, promoting sustainable development without imposing rigid external conditions.

In his essay *Rewriting the European Economy* [16], Joseph Stiglitz proposes an alternative model for the economic management of Europe, moving away from rigid austerity policies and external impositions. Among other things, he promotes flexibility in sustainable development[47] and attention to local needs.[48] Similarly, Amartya Sen, Indian philosopher and economist, in his essay Development as Freedom, emphasizes the importance of a flexible approach to sustainable development, tailored to local specificities rather than imposed through rigid and uniform criteria [17]. Sen highlights how communities must have the power to decide how to manage resources and environmental challenges in a way that is most suitable for their reality.

### 3.7 Conclusion: Challenges and opportunities

The Common Agricultural Policy (CAP) 2023–2027 represents an ambitious and complex attempt to reconcile two seemingly conflicting needs: food security and environmental sustainability. In a global context marked by unprecedented challenges, such as climate change, health crises, and geopolitical tensions, the CAP aims to provide a regulatory framework that integrates economic, social, and environmental objectives.

The introduction of enhanced conditionality and eco-schemes highlights the growing priority given to environmental protection in the agricultural sector. However, the challenges pointed out by the European Court of Auditors, such as unclear objectives, complex regulations, and insufficient controls, cast doubt on the effectiveness of the implemented measures. These obstacles risk undermining the delicate balance between agricultural productivity and environmental protection.

The theoretical debate, enriched by the contributions of economists like Joseph Stiglitz and Amartya Sen, suggests the need for a more flexible approach that is adaptable to local specificities. Both emphasize the importance of avoiding rigid and uniform policies, instead promoting the participation of local communities in the management of resources and environmental challenges. This approach would not only foster sustainable development but also ensure greater equity and inclusiveness in agricultural policies.

Ultimately, the CAP 2023–2027, while providing a solid foundation to address current challenges, requires further interventions to ensure alignment between objectives and implementation. It is crucial that lawmakers and European institutions work to simplify the regulatory framework, strengthen control systems, and encourage policies that account for local diversity. Only through an integrated vision and effective implementation will it be possible to build a sustainable agriculture that meets the needs of the global population without compromising the environment.

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[47] This implies supporting investments in green infrastructure, technological innovation, and sectors that reduce environmental impact.

[48] This approach values regional and national particularities, rather than imposing a uniform model across Europe.

## 4. The CAP between sustainability and food security: Toward sustainable capitalism

### 4.1 Introduction: The CAP as a tool for sustainable capitalism

The new framework of the Common Agricultural Policy (CAP) aims to provide forms of payment not linked to the agricultural production directly achieved by individual farmers, limiting coupled payments to marginal cases compared to decoupled payments. Farmers are entitled to receive a series of payments (previously a single payment under Regulation 1782/2003[49]) solely for owning agricultural land suitable for grazing, cultivation, or for performing a minimum activity defined by the member state, even in the absence of direct productive activity.[50]

### 4.2 Decoupled payments and food security

In this context, the irrelevance of production choices for accessing subsidies represents a tool to steer the entrepreneurial activities of European farmers toward the market, without having crop decisions primarily depend on the European Union's production support mechanisms. Basing subsidies on non-productive variables, but linked to environmental conditions, the so-called "green conditions," seemingly impacts, as we will see, the actual productivity of European crops, with visible effects in the long term. This raises questions about how to reconcile the issue of food security, included in the 2030 Agenda[51] as a key element for sustainability, with the green logic that inspires the Green Deal and the CAP 2023–2027.

### 4.3 Environmental targets of the CAP and challenges in the agricultural sector

Agriculture, the first food production activity analyzed, raises environmental and climate concerns, especially when conducted intensively.[52] To address these issues, several targets have been set to be achieved by 2030[53] (non-legally binding):

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[49] https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CONSLEG:2003R1782:20080101:IT:PDF.

[50] Regarding the concept of agricultural activity, see the two rulings by the Court of Justice of the EU, both delivered on April 7, 2022, in case C-116/20, SC Avio Lucos srl, https://www.osservatorioagromafie.it/wp-content/uploads/sites/40/2022/04/corte-giust-C-116-20-2022.pdf?_waf=1.

[51] Sustainable Development Goals (SDGs) and the 2030 Agenda: SDG Goal 2 (End hunger, achieve food security and improved nutrition, and promote sustainable agriculture) and Goal 15 (Protect, restore, and promote the sustainable use of terrestrial ecosystems) support this approach. European regulations on conditionality align with these goals, ensuring that agricultural practices contribute to sustainable agriculture and food security.

[52] "Intensive farming" refers to an agricultural model aimed at increasing production per unit of land through the use of advanced techniques and the intensive application of inputs such as fertilizers, pesticides, and irrigation. The goal is to optimize agricultural yield, but often at the expense of biodiversity and soil health. Intensive farming has been regulated in many legal systems to try to limit its negative impacts on the environment, particularly concerning soil erosion, excessive consumption of natural resources, and chemical contamination. In Italy, the Environmental Code (Legislative Decree 152/2006) and regulations related to the management of natural resources (water, soil) govern intensive farming, imposing restrictions to prevent environmental damage and protect public health.

[53] These are quantitative targets.

- A 50% reduction in the overall use and risk of chemical and hazardous pesticides.
- A 50% reduction in nutrient losses and at least a 20% reduction in the use of fertilizers.
- Allocating at least 25% of the EU's agricultural land to organic farming.[54]

For livestock activities, concerns involve not only the environment and climate but also animal welfare and human health. Major risks include antimicrobial resistance due to the excessive use of antimicrobials in animals and non-communicable diseases, such as cancer, linked to the consumption of processed red meats [18].

### 4.4 Sustainability and competition: A delicate balance

What clearly emerges is the European Union's focus, through quantitative targets and regulations governing the matter, on issues that go beyond mere agricultural production, both at the plant level (cultivation) and the animal level (livestock farming). The goal is to "ensure a resilient and sustainable use of the EU's natural resources."[55]

However, this aspect can also be considered from another perspective: the relationship between sustainability and competition. Before evaluating this issue, it is useful to make a preliminary point: the European economic system, as outlined by the Treaty on the Functioning of the European Union (TFEU),[56] has a strong liberal orientation and trust in market logic, but it also defines certain limits. For example, Article 101 of the TFEU prohibits "any agreement between undertakings, decisions by associations of undertakings and concerted practices that may affect trade between EU countries and that could prevent, restrict, or distort competition."

In this context, Article 210-bis, introduced by EU Regulation 2021/2117 within the basic Agricultural Regulation (Reg. 1308/2013), plays a key role. For the first time, it stipulates that certain sustainability agreements between specific economic operators may be exempt from the application of Article 101, paragraph 1, TFEU.[57] This provision was introduced "to support the transition to a sustainable food system in the European Union and strengthen the positions of producers in the agri-food supply chain." It stands outside the traditional model provided by Article 101, paragraph 3, TFEU,[58] and the block exemption regulations.

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[54] The achievement of the first target is supported by several legislative actions listed in the Action Plan, concerning: the revision of implementing regulations related to plant protection products containing biological active substances to facilitate their market entry, which took place with a package of regulations in August 2022 (EU Reg. 2022/1458; EU Reg. 2022/1439; EU Reg. 2022/1440; and EU Reg. 2022/1441).

[55] An initiative presented by the Commission in the overall context of the Green Deal.

[56] Inserted with the Lisbon Treaty in 2007.

[57] Article 101, paragraph 1 of the TFEU (Treaty on the Functioning of the European Union) prohibits any agreement between undertakings, decisions by associations of undertakings, and concerted practices that affect trade between EU countries and could prevent, restrict, or distort competition.

[58] Article 101, paragraph 3, acknowledges that certain restrictive agreements may create objective economic benefits that offset the negative effects on competition distortion, and allows those agreements to be exempted from such prohibitions.

### 4.5 The green new deal and sustainable capitalism

The approach of Article 210-bis is part of a set of regulatory changes aimed at promoting a sustainable economy in the European Union, altering in certain respects some of the logic of modern capitalist development. According to some,[59] the climate emergency can only be addressed through a "Green New Deal." This plan envisions a future based on ecological transition, with sacrifices in consumption and improvements in quality of life, such as accessible transportation, reduced inequalities, and decreased urban pollution [19].

Just as Keynes,[60] in his time, proposed state intervention to counterbalance the imbalances and crises of the economic system [20] today, there is a need for a similar approach, but with a sustainable focus.[61] Therefore, Article 210-bis does not conflict with the development of a "healthy[62]" capitalism, but rather redefines its logic to protect sustainable capitalism.

In this perspective, business aggregations can be effective tools not so much for increasing production, but for enhancing its sustainability, in a context where production must comply with environmental protection constraints. The Green Deal strategy indeed includes non-binding targets to be achieved by 2030 to improve the sustainability of agriculture, including the following:

- Reducing overall sales of antimicrobials used in livestock and aquaculture.
- Reducing the overall use of chemical pesticides and the most hazardous ones, as well as the associated risks.
- Reducing nutrient losses due to the use of fertilizers.
- Increasing the area dedicated to organic farming.
- Expanding areas dedicated to landscape elements with high biodiversity.[63]

### 4.6 Food security and sustainability: A possible coexistence

The complexities of reconciling food security and sustainability can be addressed through changes to the structure of capitalism and the rules that have characterized it

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[59] This refers to the Canadian writer and activist Naomi Klein, a highly influential author known for her criticism of neoliberalism and capitalism, particularly in relation to environmental issues. The author critiques both neoliberal economic policies and the insufficient scope of moderate green proposals. Her perspectives will likely continue to influence the debate on the Green New Deal, pushing it toward a vision of systemic change that challenges existing economic models in favor of a more equitable and sustainable future.

[60] John Maynard Keynes (1883–1946) was a British economist whose ideas significantly changed the theory and practice of macroeconomics. He is best known for his work during the Great Depression, particularly for the theory that government intervention in the economy is necessary to stabilize economic fluctuations and ensure full employment.

[61] An approach that has already been adopted by the legislator for some time.

[62] In which the creation of large economic-financial hubs that distort the competition game is protected.

[63] https://eur-lex.europa.eu/legal-content/IT/TXT/PDF/?uri=PI_COM:C(2023)8306.

since the second half of the twentieth century.[64] Legislative interventions, such as Article 210-bis of EU Regulation 1308/2013 or decoupled payments, respond to a deeply transformed socio-economic context, also due to the rapid technological developments.

On the one hand, the reduction of coupled payments diminishes the role of direct production logics, challenging the centrality of food security. On the other hand, the possibility for farmers to deviate from Article 101 TFEU, thanks to Article 210-bis, allows for greater efficiency in green practices and, indirectly, in food security. This connection is evident, as conditionality[65] encourages farmers to adopt practices that optimize production while also preserving the ability of agricultural land to continue producing sustainably.[66]

Food security, in fact, is not only about the availability of food, but also its quality and the ability of the land to remain productive over time. In this context, production coordination measures not only stabilize prices but also ensure an adequate level of production to meet domestic demand and prevent market crises that could compromise global food security.

The Common Agricultural Policy (CAP) represents an innovative and ambitious approach aimed at balancing seemingly opposing needs: food security and environmental sustainability. Through the transition from coupled to decoupled payments and the promotion of “green” agricultural practices, CAP 2023–2027 seeks to align production logics with global environmental challenges, while simultaneously safeguarding the ability of agricultural land to continue producing food in the long term.

### 4.7 Sustainable development and the transformation of capitalism

The introduction of Article 210-bis in Regulation (EU) 1308/2013 is emblematic of this transformation, allowing sustainability agreements among economic operators that bypass traditional competition restrictions. This tool not only promotes sustainable practices but also redefines some of the foundations of European capitalism, adapting them to the needs of an ecologically responsible economy. In a context inspired by the Green New Deal, the focus shifts from increasing production to the sustainability of production itself, ensuring higher environmental standards and fostering resilient agriculture.

Challenges related to the relationship between food security and sustainability require a rethinking of economic rules and legislative support. Conditionality and incentives for sustainable practices demonstrate that food security is no longer just a

[64] The so-called laissez-faire, whose regulation has seen numerous interventions from both the EC and later the EU.

[65] Within the framework of the CAP 2023–2027, conditionality represents a set of requirements and obligations that farmers must comply with in order to benefit from direct payments and other forms of financial support.

[66] Sustainability is here considered as the balance between economic, social, and environmental objectives, with the aim of ensuring long-term prosperity without depleting resources or harming future generations. “Producing food sustainably” thus involves following a set of principles that balance economic, social, and environmental needs, with the goal of ensuring food production that does not compromise natural resources, biodiversity, or human health in the long term.

matter of quantity but also of quality and resilience within the agricultural system. The measures adopted not only stabilize markets but also protect the productive capacity of land, preventing crises that could jeopardize global food security.

### 4.8 Conclusions: The CAP as a model for sustainable development

Ultimately, the path outlined by the Common Agricultural Policy (CAP), with the integration of legislative tools such as Article 210-bis, shapes a vision of sustainable capitalism that, though complex, offers a concrete pathway to reconcile environmental, economic, and social objectives. However, its effectiveness will depend on the ability of Member States and operators to implement these regulations consistently and integratively, thereby ensuring the long-term sustainability of the European agricultural system.

## 5. Sustainable development and modern capitalism: A balance between food security, green logics, and economic competitiveness

### 5.1 Introduction: The challenge of sustainable development in modern capitalism

The question we ask, in conclusion to the previous reflections, is whether sustainable development, within the framework of green logics, can truly reconcile with economic development as it has been conceived up to the latest revolution of modern capitalism. Furthermore, how food law can address the challenge of balancing, on the one hand, food security, and on the other hand, the sustainability of the planet's natural ecosystems.

### 5.2 Obstacles and opportunities of sustainable development

When considering on a macroscopic scale, some contradictions related to the theme of sustainable development immediately emerge as follows:

- The difficulty of achieving a balance between economic growth and environmental protection.
- Diverging interests among different stakeholders, such as businesses, governments, and local communities.
- Issues related to financing sustainable initiatives.
- Lack of awareness, ethics, and political will.
- The disproportionate impact of environmental and social challenges on the most vulnerable groups, which exacerbates existing inequalities.

### 5.3 Examples of sustainability integration into capitalism

Considering these challenges, it can be stated that only through a collective effort will it be possible to build a sustainable future for all. However, one positive aspect, from a macroscopic perspective, concerns the ability of the competitive logics of "classical[67]" capitalism to integrate sustainability-related elements.

For example:

- Labeling of sustainable foods has gained significant competitive value, with a notable price mark-up starting in 2024.[68]

- Financial institutions are increasingly valuing companies that improve their environmental performance, as evidenced by the focus on the three scopes of CO2 emissions (Scope 1, 2, and 3).[69]

- Sustainability reports are becoming central as tools for communicating value to business stakeholders.[70]

These elements suggest that sustainable development is finding its realization within the very logics of the traditional economic system, using the means offered by capitalism to promote a sustainable transition.

### 5.4 Stakeholder capitalism according to Stiglitz

Stiglitz proposes an economic system that takes into account the interests of all stakeholders involved in the production process (the so-called stakeholder capitalism): workers, local communities, consumers, suppliers, the environment, and society at large.

He specifically proposes the following points:

- Overcoming profit as the sole objective: The stakeholder capitalism model requires companies to consider their social and environmental impact, in addition to financial returns.

- Centrality of public policies: Governments must create a regulatory framework that incentivizes responsible business behavior, discourages short-term thinking, and rewards sustainability.

- Redistribution of economic benefits: Stiglitz argues that the value produced by companies should be distributed fairly, avoiding a disproportionate share of profits going to shareholders and executives.

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[67] We refer to the magnum opus of Ref. [21]. It was originally published in 1776 and has been translated into various editions.

[68] Nielsen Source.

[69] Emissions are divided into three categories: scope 1, which includes direct emissions controlled by the organization; scope 2, which concerns indirect emissions related to the production of electricity, steam, or heat; and scope 3, which includes indirect emissions from the company's value chain.

[70] Thus, through the enhancement of activities related to sustainability, which are assigned value in terms of price or other typical capitalist logics.

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| Focus area | Metric | Source |
|---|---|---|
| Overcoming profit as the sole objective | Greenhouse gas emissions (tons of CO2 equivalent) | World Economic Forum (WEF) |
| Overcoming profit as the sole objective | Total energy consumption (GJ) and % from renewable sources | World Economic Forum (WEF) |
| Centrality of public policies | Compliance rate with environmental regulations (%) | World Economic Forum (WEF) |
| Centrality of public policies | Investments in sustainable initiatives (total value and % of the budget) | World Economic Forum (WEF) |
| Redistribution of economic benefits | CEO pay ratio/average employee salary | World Economic Forum (WEF) |
| Redistribution of economic benefits | Percentage of economic value distributed to stakeholders | World Economic Forum (WEF) |
| Sustainability and innovation | Share of revenues from sustainable products or services (%) | World Economic Forum (WEF) |
| Sustainability and innovation | Reduction of ecological footprint (resources or waste % per year) | World Economic Forum (WEF) |

**Table 2.**
*Some metrics for the stakeholders capitalism.*

- Sustainability and innovation: Stakeholder-oriented capitalism promotes sustainable and innovative practices, considering the long-term well-being of the entire community (**Table 2**) [22].

### 5.5 Contradictions and challenges in sustainable development

By analyzing sustainability through the lens of food security and green logics, we can identify some key points of balance and reconciliation:

1. The goals of the 2030 Agenda, in their integrated vision, allow for the respect of both green logics and those related to food security, as explicitly stated in Goal 2.[71]

2. Food security and green logics find a point of equilibrium through decoupled payments and sustainability agreements provided by Article 210-bis of EU Regulation 1308/2013. These regulatory tools improve the efficiency of business groups, yielding benefits in terms of both sustainability and long-term production quantities.

3. The virtuous aspects of the secondary sector, such as the transition to more sustainable industrial processes, will necessarily have positive impacts on the primary sector, driving change and promoting a more balanced transformation.

[71] Goal 2 of the 2030 Agenda focuses on "Ending hunger, achieving food security, improving nutrition, and promoting sustainable agriculture." This goal addresses the challenges related to food poverty and hunger worldwide, aiming to ensure that everyone has access to sufficient and nutritious food, particularly in vulnerable regions.

## 5.6 Conclusions: Sustainable development as the evolution of capitalism

The reflections developed show how sustainable development can be integrated, albeit with difficulties and contradictions, into the logics of the traditional economic system. The main challenges involve balancing economic growth with environmental protection, aligning the interests of the involved actors, and adopting policies capable of promoting a fair and inclusive transition.

However, concrete examples demonstrate that capitalism itself, through its competitive mechanisms, can serve as a tool to incentivize sustainability. Sustainable labeling, the recognition of environmental performance by financial institutions, and the growing importance of sustainability reports highlight how sustainability is becoming a competitive advantage. This confirms that green logics can find a place within a traditional economic system, evolving without necessarily abandoning its fundamentals.

The analysis of the synergies between food security and environmental sustainability also reveals that regulatory tools, such as decoupled payments and sustainability agreements provided by Article 210-bis of EU Regulation 1308/2013, represent an effective point of balance. These tools not only foster sustainability but also ensure sufficient long-term productivity, contributing to a balanced transformation of economic sectors.

Ultimately, sustainable development is not an alternative to the existing economic model but its evolution. Through targeted regulatory interventions and growing collective awareness, it is possible to build a future in which food security, environmental protection, and economic efficiency coexist, thus ensuring the well-being of both present and future generations.

## 5.7 Possible strategic next steps

- Integration of sustainability into agricultural models through the CAP and the Green Deal (Europe).

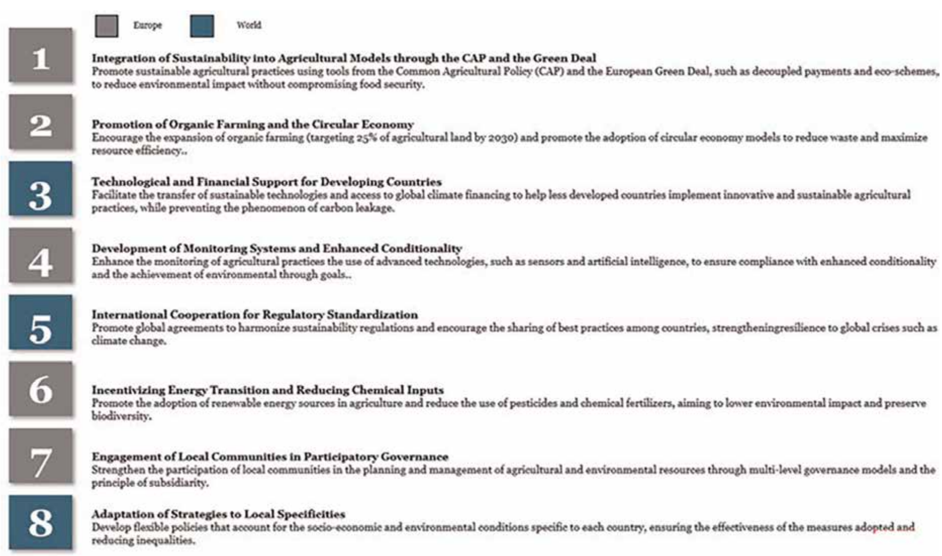


**Figure 5.**
*Possible next steps for Europe and the whole world.*

- Promotion of organic farming and circular economy (Europe).
- Technological and financial support to developing countries (World).
- Development of monitoring systems and reinforced conditionality (Europe).
- International cooperation for regulatory standardization (World)
- Encouragement of energy transition and reduction of chemical inputs (Europe).
- Involvement of local communities in participatory governance (Europe)
- Adaptation of strategies to local specificities (World) (**Figure 5**).

This sequence aims to strengthen institutional and technological foundations in Europe before expanding strategies globally, ensuring an inclusive and sustainable approach.

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*Edited by Vijay Singh Meena, Jai Prakash Jaiswal, Dinesh Jinger and Venkatesh Paramesh*

*Triticum – The Pillar of Global Food Security* provides a comprehensive and timely examination of the scientific, agronomic, and socio-economic factors influencing the future of wheat. As the backbone of global food systems, wheat must adapt to a changing climate, increasing biotic and abiotic stresses, and growing demands for sustainability and nutritional security. This edited volume explores cutting-edge approaches in integrated pest management, genetic improvement, stress resilience, and sustainable crop practices, offering valuable insights for researchers, practitioners, and policymakers. It examines the intersection of wheat breeding, phenology, climate adaptation, food safety, and biofortification through the lens of emerging technologies, including genome editing and next-generation sequencing. The book also addresses broader themes such as green capitalism, circular economy in agriculture, and the critical role of wheat in combating hidden hunger. With a global perspective and interdisciplinary approach, this volume is an essential resource for anyone interested in advancing sustainable wheat production and enhancing food security in an era of rapid environmental and demographic change.

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