

Biotechnology as a Key Driver in Achieving Saudi Arabia's Food Security

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Abstract

Food security is a critical global issue, particularly in regions facing environmental and resource challenges. The Kingdom of Saudi Arabia is among the world's biggest importers of food. In the Kingdom, the quest for sustainable food production is complicated by arid climatic conditions, limited arable land, and scarce water resources. By 2050, all its domestic needs are predicted to be imported. As the Kingdom strives to reduce its reliance on food imports and bolster local production, biotechnology emerges as a transformative tool. By leveraging advancements in genetic engineering, sustainable agriculture, and biotechnological innovation, Saudi Arabia can address its unique challenges while aligning with the goals of Vision 2030. This literature review explores the role of biotechnology in enhancing food security in Saudi Arabia. It examines the current state of food security in the Kingdom, highlights the potential of biotechnological solutions such as genomics, proteomics, metabolomic, Marker-assisted selection (MAS), next-generation sequencing (NGS) technology and genetic engineering, and discusses ongoing initiatives and future prospects. This review offers alternative practices and approaches that Saudi Arabia can implement in the current environment to increase domestic food production and ensure food security in the Kingdom. This review underscores the importance of biotechnology as a key driver in achieving sustainable food systems.

Keywords

The Kingdom of Saudi Arabia, Food Security, Genetic Mechanisms, Biotechnology Techniques, Drought, Salinity

1. Introduction

Food security has been a strategic concern for Saudi Arabia for more than half a century. The Kingdom is one of the largest food importers globally, sourcing ap-

proximately 80% of its food from international markets [1]. This reliance highlights the vulnerabilities of its domestic food supply chain and underscores the importance of sustainable agricultural practices. This dependency stems from the Kingdom's environmental constraints, as Saudi Arabia's harsh desert climate is characterized by extremely high temperatures, averaging 45°C in summer, and low annual rainfall, typically less than 100 mm [2]. These factors severely limit traditional agricultural practices, such as rain-fed farming, and necessitate innovative approaches to food production. Additionally, the lack of resources, particularly water, is a major challenge to Saudi food security because the majority of the country's water comes from desalination plants. The Kingdom ranks among the most water-stressed countries globally by 2050, with limited renewable water resources [3]. According to (Al-Hussayen, 2007) agriculture, accounting for over 80% of water consumption, heavily relies on non-renewable fossil groundwater [4]. The depletion of these reserves raises concerns about the sustainability of agricultural expansion. Furthermore, another significant obstacle to Saudi Arabia food security is the shortage of fertile land with 90% of its land is unsuitable for farming. The widespread presence of saline soils reduces agricultural productivity and poses a barrier to crop cultivation [5]. Moreover, population growth and urbanisation pose a serious threat to Saudi Arabia food security. The population of Saudi Arabia has grown significantly over the past few decades, reaching approximately 35 million in 2023 [6]. Urbanization and rising living standards have increased the demand for diverse and high-quality food products, such as wheat, rice, and dairy products to meet domestic demand, further straining the domestic food system. The Saudi Arabia economic dependency on imports exposes the Kingdom to global supply chain disruptions, fluctuating prices, and geopolitical risks. The COVID-19 pandemic and recent geopolitical conflicts have highlighted the fragility of this reliance on external food sources. Despite efforts to boost local production through advanced agricultural techniques and investment, achieving self-sufficiency remains a significant challenge. Agriculture is the foundation of a country's economic strength. If agricultural practices fail to achieve self-sufficiency in food production, the nation's stability and security will be jeopardized. Hence, attaining food security requires addressing agricultural challenges and ensuring that farmers are aware of modern agricultural technologies that are essential for improving productivity. The purpose of this review is to assess the current state of food security in relation to agricultural production and consumption as well as discussion the role that biotechnology techniques might play to help achieve food security with the resources at hand.

2. Overview of Food Security in Saudi Arabia

2.1. Current State of Food Security in Saudi Arabia in Relation to Agricultural

Food security, as defined by the Food and Agriculture Organisation (FAO) in 2010, is “a situation that exists when all people, at all times, have physical, social,

and economic access to sufficient, safe, and nutritious food that meets their dietary needs and food preferences for an active and healthy life” [7].

The majority of agricultural commodities in desert nations—including The Kingdom of Saudi Arabia (KSA) are imported from other nations since indigenous production is insufficient. Food security can be enhanced by promoting traditional crops that thrive in dry climates, such as wheat, barley, sorghum, and millet (FAO) in 2010 [7]. Additionally, since dates are one of Saudi Arabia’s top products, it is essential to explore further research opportunities in this area [8]. The production and availability of barley and wheat in the Kingdom are outlined in **Table 1**. As observed, the Kingdom has not yet produced barley and is primarily reliant on imports. However, Saudi Arabia’s wheat production reached its highest recorded level in 2012, at 783,974 tonnes. Since then, production has steadily declined, dropping to an all-time low of 0 tonnes in both 2016-2017 and 2018. It recovered to 538,436 tonnes in 2022, as illustrated in **Table 1** [9].

Table 1. The quantities of barley and wheat received from farmers and the manufactured quantities of flour and fodder in different years in the Kingdom. Source: Ministry of Agriculture (2024). Quantities are in thousand tons.

Year	Quantities of Grains Received from Farmers		Manufactured Quantities	
	Wheat (tons)	Barley (tons)	Flour (tons)	Feed (tons)
2012	783,978	0	2,524,365	416,995
2013	604,305	0	2,555,976	466,951
2014	689,551	0	2,544,003	535,816
2015	722,333	0	2,670,487	566,235
2016	0	0	2,778,645	418,012
2017	0	0	2,739,697	405,303
2018	0	0	2,604,913	415,083
2019	202,150	0	2,626,064	461,996
2020	386,645	0	2,650,111	555,858
2021	576,024	0	2,637,821	632,425
2022	538,436	0	3,423,882	737,894

The Kingdom’s yearly wheat crop imports, exports, and consumption are presented in **Table 2** [9]. It is clear that, the Kingdom has not yet exported any wheat, and its domestic production is insufficient to meet demand, mostly relying on imports. In 2022, Saudi Arabia consumed 4482 tonnes of wheat, the most ever recorded amount, while importing 3345 tonnes, as **Table 2** illustrates. The import of wheat, an essential crop, places a significant strain on the Saudi Arabia’s budget [10]. To alleviate the burden of imports, it is crucial to focus on agricultural research and extension initiatives.

The availability of different food items throughout the Kingdom is displayed in **Table 3**. It is evident that the Kingdom exports a large number of its crops to other nations and has achieved greater than 100% self-sufficiency in several crops, including dates, okra, eggplant, cantaloupe, and figs. Some other varieties, such as bananas, citrus fruits, and pomegranates, are still significantly lacking at less than 30%, and their local output is insufficient to meet demand, primarily relying on imports **Table 3** [9].

Table 2. shows the annual consumption, trade of wheat crop in the Kingdom in different years. Source: Ministry of Agriculture (2024). Quantities are in thousand tons. The decrease in imported quantity in 2015 is due to the government's approval for resuming local wheat purchasing from farmers that year, which reduced the need for imports.

Year	Wheat Consumption	Imports	Exports
2012	3164	2212	0
2013	3210	2530	0
2014	3200	3124	0
2015	3354	2715*	0
2016	3504	3780	0
2017	3479	3108	0
2018	3359	3218	0
2019	3356	3271	0
2020	3422	3260	0
2021	3477	3050	0
2022	4482	3354	0

Table 3. Self-sufficiency ratio of plant products in the Kingdom for the Year 2022. Source: Ministry of Agriculture (2024).

Crop Type	Local Production (tons)	Imports (tons)	Exports (tons)	Self-sufficiency Ratio (%)
Potatoes	605,000.00	150,252.84	615.82	80
Tomatoes	658,540.00	329,365.67	271.19	67
Onions	310,000.00	399,095.21	1,850.77	44
Zucchini	71,550.00	20,674.74	2,200.02	80
Cucumbers	204,720.00	2977.37	902.76	99
Green Pepper	119,780.00	49,592.94	3,977.37	72
Carrots	38,951.85	45,592.14	7,200.51	50
Okra	25,590.00	206.30	1,112.5	103
Watermelon	505,000.00	35,339.78	406.40	95

Continued

Eggplant	118,850.00	1880.53	1380.85	105
Cantaloupe	5811.55	5810.69	7.50	73
Cauliflower	21,244.55	11,424.95	3453.72	73
Melon	55,457.67	6.00	8.62	100
Pumpkin	69,792.53	6405.22	86.70	92
Beans	12,028.73	1836.27	626.65	91
Dates	1,610,731.61	7893.11	321,149.55	124
Lemon	122,400.75	736,599.26	21,377.87	15
Mangoes	89,499.83	79,810.37	2908.50	54
Grapes	110,500.00	80,429.42	731.96	58
Bananas	22,400.00	317,930.64	1693.33	7
Fig	28,049.63	365.78	3153.29	111
Pomegranate	31,199.70	86,688.05	2747.07	27
Papaya	4420.00	362.77	504.08	103

2.2. The Kingdom Main Constraints on Agricultural Productivity

According to Fahad *et al.* [11], non-biological stresses such as drought, high temperatures, salinity, and nutrient deficiencies are the main constraints on agricultural productivity in desert regions. These factors have a detrimental effect on the growth and development of plants, leading to a notable decrease in biomass, crop yield, and quality, ultimately resulting in substantial losses in agricultural production. According to Baeshen *et al.* [12], 2,150,000 square kilometers are occupied by the Kingdom of Saudi Arabia. The primary abiotic stress that crops in Saudi Arabia commonly face in the field is the combined pressure of drought and heat [12]. Fiaz *et al.* [13] highlighted that Saudi Arabia cannot utilize its extensive land for farming to satisfy local food needs and relies on importing it. Because of the continuous abiotic stress, especially the drought, heat, and salinity in Saudi Arabia, a large part of the country is deserted and remains uninhabited and unsuitable for agriculture. Furthermore, Fiaz *et al.* [13] have reported that, during 2013, 660,145 tons of wheat were grown within 102,613 hectares, and 2,117,052 tons of wheat were brought in from other countries.

It has commonly been assumed that crop development is limited by a range of factors, including biotic, abiotic, and socioeconomic constraints. One of the most crucial abiotic factors that restrict crop growth on a global scale is the availability of water [14]. Consequently, comprehending the physiological processes and genetic regulation of drought in cultivated plants is essential to improving crop yields in arid and semi-arid regions [14]. As reported by Kole [15], the drought has a significant impact on wheat and barley yields. Specifically, drought reduces wheat yield by 61% and barley yield by 53%. Among cereal crops, sorghum is

known for its exceptional drought tolerance. It features a dense and deep root system, which allows it to reduce transpiration through leaf rolling and stomatal closure. Furthermore, sorghum has the ability to reduce its metabolic processes to near dormancy during extreme drought conditions. Consequently, sorghum can survive during dry periods and resume growth once soil moisture becomes available. Despite its drought tolerance, sorghum still experiences yield losses of 60% - 90%, depending on the severity of the drought [15]. There are relatively several studies in this area that have highlighted that different plants have developed ways to deal with various abiotic stresses such as drought and heat in their extreme natural habitats [12] [16]. These plants have successfully adapted by triggering the activation of multiple stress genes, generating various metabolites, and initiating signaling and biochemical pathways to alleviate any harm caused by stress [16].

3. Genetic Mechanisms Regulate Drought Tolerance in Crop Plants

To illustrate the impact of stress on gene expression, Rizhsky *et al.* [17] [18] observed that stress can induce modifications in plant morphology, including stomatal conductance and leaf and root size, as well as physiological and molecular changes such as the generation of antioxidants and osmotic adjustment to withstand abiotic stress. The primary focus of numerous studies on drought-stressed plants has been identifying and understanding adaptive metabolic changes and assessing their role in drought resistance. These have been key areas of focus in research on plants under stress for a considerable period. A study conducted by Amelework *et al.* [19] revealed that drought is a significant factor that impacts crop production globally. As climate change increases the frequency of drought and flood occurrences, it is expected to cause a change in the severity and frequency of drought events. By 2050, it is estimated that 67% of the world's population will experience water shortages. Therefore, improving the drought tolerance of food crops is a crucial objective in many crop-breeding programs [20].

A recent literature review was carried out by Belete [21] that mentioned that understanding drought resistance in crop plants involves unraveling the complex interplay of genetic and physiological factors. Identifying the specific genes and pathways associated with this trait is essential for developing improved crop varieties through targeted breeding strategies. In 2021, Prasad *et al.* [22] pointed out that by integrating genetic insights with an understanding of physiological mechanisms like water uptake and stress response, breeders can enhance crop resilience to drought conditions. This holistic approach is crucial for ensuring food security in the face of climate change [23]. Kebede *et al.* [20] highlighted that understanding the genetic mechanisms governing drought tolerance in crop plants remains limited. Due to the complexity of drought tolerance, which involves multiple genes and is influenced by the timing and severity of moisture stress, studying, and characterizing this trait pose significant challenges.

However, several studies have indicated that a range of plant species have de-

veloped strategies to tackle various environmental stresses like drought and extreme heat in their natural surroundings, including the development of larger and deeper root systems [23], regulation of stomatal closure to minimize water loss [24], accumulation of compatible solutes and protective proteins [25], and elevation of antioxidant levels [26]. While the identification of drought-resistant traits has often been described as “complex” [27]. Other studies mentioned different strategies that related to previous methods by boosting the activity of different stress-responsive genes, producing specific metabolites, and triggering signaling pathways and biochemical reactions to counteract stress-induced harm [28]. All these processes involve modifying the movement of metabolites through various pathways. These changes in plant stress tolerance occur at the molecular, cellular, tissue, whole plant, and physiological levels. Recent research suggests that ROI (reactive oxygen intermediates) may be essential for plant cells as signaling molecules that control gene expression in response to stress or pathogen infection [17, 18]. As per Agarwal *et al.* [29], plants can provide stress tolerance through molecular responses to abiotic stress that involve perception, signal transduction, gene expression, and ultimately, metabolic changes. When abiotic stressors occur, several genes are transcription stage activated. These variable genes’ products are believed to enhance stress tolerance through the production of crucial metabolic proteins and regulating genes downstream [30].

Limited information exists regarding the genetic basis of these diverse mechanisms. However, various studies have documented substantial genetic variation within various plants, such as sorghum germplasm, regarding their response to drought. Numerous traits associated with drought resistance have been identified and mapped; the stay-green trait is acknowledged as the most pivotal drought resistance trait in sorghum [31]. Genotypes showing various degrees of the stay-green trait have been identified [32] [33]. However, the heritability of this trait varies across different genotypes. In some cases, it seems to be governed by dominant genes (e.g., B35), while in others, it appears to be recessive (e.g., R9188) [34] [35]. Another study on the stay-green trait in line B35 reported its modulation by a major gene, with the level of dominant gene action influenced by the environmental conditions under which the materials are assessed [36]. A separate investigation into the genetic underpinnings of osmotic regulation found notable variation among various sorghum genotypes [37]. In a biparental progeny genetic analysis, it was discovered that two distinct major genes (OA1 and OA2) play a role in regulating osmotic adjustment in sorghum [38]. Conversely, in a different population set, a monogenic inheritance pattern was observed in other studies to govern the trait (2). In addition, Cheng *et al.* [39] reported that the expression of Ethylene Response Factor 1 (ERF1) (AT3G23240) in *A. thaliana* was significantly increased under salt and drought stress conditions. Overexpression of ERF1 has been shown to improve drought, heat, and salt tolerance in *A. thaliana*. The wheat ERF1 (TaERF1) gene transcription was also triggered by various biotic and abiotic stresses [40].

4. Biotechnological Approaches for Drought Improvement

Wagaw [31], a recent review of significant systems of drought tolerance in sorghum (*Sorghum bicolor* L.) and breeding mechanisms provides a strong critique of various biotechnological methods for enhancing drought tolerance. The primary biotechnological approaches for drought improvement include genomics, proteomics, Marker-assisted selection (MAS), next-generation sequencing (NGS) technology metabolomics, and genetic engineering, among others. Mitra [41] demonstrated that gene transformation techniques have been utilized in crop plants to identify genes associated with drought resistance and transfer them. Two main strategies, namely targeted and shotgun approaches, are employed in genetic engineering to develop transgenic plants with enhanced drought resistance.

4.1. Plant Functional Genomics

Plant functional genomics has emerged as a burgeoning scientific field dedicated to studying the roles and functions of genes. Manavalan *et al.* [42] have attempted to prove the significant effects of microarray-based gene expression profiling in pinpointing genes that govern drought resistance in crops. Furthermore, transcriptomic analysis has revealed that most drought-responsive genes can be categorized into ABA-dependent, and DREB2A/ubiquitination-related mechanisms. In addition, genes involved in the synthesis of osmolytes such as proline, amino acids, and amines like glycine, betaine, and polyamines exhibit differential expression patterns in response to drought stress [42].

4.2. Proteomics

In addition, Manavalan *et al.* [42] have highlighted the relevance of the roles and functions of genes by using proteomics, which involves the systematic examination of expressed proteins and serves as a valuable tool for identifying proteins engaged in cellular processes. It offers insights into the abundance of gene products, their isoforms, and the post-transcriptional modifications that regulate protein activation. Proteomics has led to the identification of numerous drought-responsive proteins across various plant tissues [42]. Beyond gene transcripts, proteins, and metabolites, small RNAs such as miRNAs and siRNAs are also implicated in adaptive responses to abiotic stresses [43]. While Mitra [41] focused on molecular markers such as restriction fragment length polymorphism (RFLP), random amplified polymorphism (RAPD), and isozyme, they will facilitate the development of drought-resistant genotypes more effectively as their expressions are independent of environmental effects.

4.3. Marker-Assisted Selection (MAS)

One study by Ribaut *et al.* [43] examined the trend in Marker-assisted selection (MAS), which is highly valuable in QTL analysis because it enables the identification of genes responsible for superior performance across a wide range of environments. After identification of the molecular markers associated with yield or

other morphological traits related to drought resistance, those markers could be used as a selection criterion for drought resistance. The application of marker-assisted selection in evolving drought-resistant genotypes is in an experimental stage, more specifically the identification of RFLP markers associated with osmotic adjustment, stay green, and root traits. Some authors have mainly been interested in genome-wide association analysis, which is considered another powerful tool used to identify genes that are linked to phenotypic traits with higher resolution as compared to QTL analysis. However, there are only a few studies that describe its current application in vegetables. Most of the GWA studies conducted on tomatoes are related to fruit traits such as flavor, quality, and lycopene [44]-[46]. Other researchers, however, have identified several genomic regions associated with drought tolerance during both pre-flowering and post-flowering stages that have been identified [22]. However, Paterson *et al.* [47] have sequenced the sorghum genome, enabling the examination of genome-wide gene expression patterns in response to various abiotic stresses using techniques like microarray or RNA-Seq analysis [48]-[50]. These studies resulted in the identification of drought stress-responsive genes and their regulatory elements [51].

4.4. Next-Generation Sequencing (NGS)

Others have emphasized the significance of advancements in next-generation sequencing (NGS) technology, which provides abundant opportunities for analyzing transcriptomic and genomic data to comprehend abiotic stress tolerance in non-model plants lacking a reference genome [52]-[55]. For example, the de novo genome assembly of *Thellungiella parvula*, which thrives in saline and resource-poor environments [56]; transcriptome analysis of *Rhazya stricta*, a plant species found in arid zones [57]; transcriptome analysis of the desiccation-tolerant plant *Craterostigma plantagineum* [58]; and studies on abiotic stress tolerance in *Rhizophora mangle* and *Heritiera littoralis* [59].

4.5. Metabolomic

Metabolomics has mostly studied the organic molecular compounds (metabolites) present in or produced by organisms, tissues, and cells. Metabolomics is currently widely employed in plant science as an important biotechnological approach for molecular biology research. It includes a diverse set of analytical techniques for identifying organic molecular metabolomic materials. Metabolic fingerprinting, metabolite profiling, and targeted analysis are a few examples [60]. Metabolomics approaches were previously utilised to study plant drought, salinity and heavy metal tolerance and response [61]-[64]. Bowne *et al.* have employed a targeted GC-MS approach to categorise chemicals that differed among three bread wheat cultivars with varied drought tolerance [61]. Metabolomic techniques have also been used to examine the molecular differences between drought-sensitive and drought-tolerant poplar species, indicating the promise of metabolomics in understanding drought resistance mechanisms [62]. Morphological structure and proteome investigations

of other plants, such as *Morus alba* L. and cucumber, have also helped us understand plant responses to short-term drought and re-watering [60] [63].

5. Conclusion and Perspective

Environmental stressors, notably drought, reduce plant growth and production, putting global food security at risk. The Kingdom of Saudi Arabia has made great social and economic progress in recent years. With limited land and water resources, the available food supply from domestic production is significantly less than the household's daily needs, severely reducing agricultural production. Improving agricultural productivity can lead to a long-term boost in crop production. There is a large gap between demand and output of agricultural products in the Kingdom, which must be bridged by the application of Biotechnology technology such as genomics, proteomics, Marker-assisted selection (MAS), next-generation sequencing (NGS) technology metabolomics, and genetic engineering. The necessity for the country to become food secure by implementing some of the primary approaches mentioned above. To reduce the economic and social costs of diet-related products. Thus, one of the key implications for sustainable crop production in the Kingdom is the creation of drought and salinity-resistant crops. To deal with environmental cues like dryness, plants have developed a number of cellular and molecular adaptation methods. The underlying genetic and molecular pathways of drought tolerance are still a developing field in botanical biology. Biotechnology approaches seem to play an important role in managing drought and salinity in various plant species. The overall advancement of research on these approaches has disclosed its crucial role in future food security.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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