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Editorial

Developments, Applications, and Innovations in Agricultural Sciences and Biotechnologies

Anzhen Qin and Dongfeng Ning *

Institute of Farmland Irrigation, Chinese Academy of Agricultural Sciences, Key Laboratory of Crop Water Use and Regulation, Ministry of Agriculture and Rural Affairs, Xinxiang 453002, China; qinanzhen@caas.cn
* Correspondence: ningdongfeng@caas.cn; Tel.: +86-373-3393321

1. Introduction

The global population is projected to reach approximately 10 billion by 2050, and the demand for food is expected to increase by 60–70% [1]. In order to sustain this ever-growing population, agricultural technologies have continuously developed under the great efforts of scientists and scholars worldwide [2]. Among these advances, biotechnology has played a significant role in improving crop resistance to drought, plant diseases, and insect pests under global warming [3]. The past two decades have witnessed remarkable advancements in bio-agricultural science, with a strong focus on sustainable farming systems, improved molecular breeding, and advanced crop management [4]. However, the natural resources required to meet the food needs of the population, such as arable land and fresh water, are becoming increasingly scarce [5]. Therefore, the future challenges faced by the bio-agricultural sector will be more complex than ever before, threatening global food security [6]. Against this backdrop, biotechnologies have emerged as critical tools to address these issues [7].

The articles reviewed in this editorial collectively present significant progress in areas such as irrigation technology, seed biotechnologies, intercropping systems, drought stress management, and renewable energy applications in agriculture. The diverse research topics underline the interdisciplinary nature of modern agricultural science, blending traditional agronomic practices with cutting-edge biotechnologies. This editorial synthesizes the key findings of the studies in this Special Issue and discusses future directions for sustainable agricultural development. It also captures the essence of advancements in biotechnologies, showcasing how scientific research and technological innovations are transforming the agricultural landscape, enabling the development of solutions to reduce water resource waste, conserve biodiversity, and guarantee food security. By summarizing irrigation technologies, crop management, seed biology, abiotic stress mitigation, renewable energy, and genetic diversity, this editorial will provide a comprehensive picture of the progress being made toward building a sustainable and resilient agricultural future. In the sections that follow, we delve into the key findings, implications, and future directions highlighted in these studies.

2. Advances in Irrigation Technologies and Water Management

Water is one of the most critical resources for agriculture, and its efficient management is essential for ensuring food security in the face of increasing water scarcity (Contribution 1). The study on micro-sprinkling irrigation systems for wheat crops presents a compelling case for adopting modern irrigation technologies that enhance WUE while

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maintaining or even increasing crop yields (Contribution 2). By improving water distribution and optimizing irrigation strategies, this technique obtains comparable crop yields to traditional strategies. These findings underscore the potential of micro-sprinkling systems to transform water management practices in agriculture. Irrigation is particularly important in regions where water scarcity threatens local food production [8]. This paper provides a meaningful example of how advanced irrigation technologies meet the dual goals of lower water consumption and higher grain yields.

2.1. Optimizing Irrigation for Water-Scarce Regions

In the North China Plain, water resources are limited, and traditional flood irrigation methods are usually inefficient and unsustainable, posing a major challenge to agricultural productivity. The findings in the paper have far-reaching implications, showing that crop water use can be reduced without sacrificing yields using micro-sprinkling irrigation with optimized border widths due to following several advantages:

Uniform soil moisture distribution: By delivering water evenly across the field, the uniformity coefficient of soil moisture increased by 25.8%. These micro-sprinkling systems minimize water wastage and ensure consistent soil moisture levels across the field, reducing the risk of over- or under-irrigation.

Optimized irrigation quotas: The study demonstrates how adjusting irrigation quotas based on crop growth stages can lead to significant water savings without compromising yield. Adjusting irrigation quotas in response to crop growth stages leads to improved WUE and higher grain yields.

Economic viability: The simplicity and cost-effectiveness of micro-sprinkling systems make this technology accessible to smallholder farmers, who are often the most vulnerable to water scarcity, particularly in water-stressed regions.

2.2. Future Directions for Research and Implementation

While the study demonstrates the efficacy of micro-sprinkling systems, their widespread adoption will require overcoming several barriers, including the initial investment cost, the need for farmer training, and the adaptation of the technology to different crop types and soil conditions. Future research should explore the integration of these systems with precision agriculture tools, such as soil moisture sensors and weather-based irrigation forecasting. Additionally, policymakers and extension services must play a proactive role in promoting these technologies through subsidies, capacity-building programs, and demonstration projects. These policy interventions and incentives will be crucial in promoting the adoption of water-efficient technologies in the NCP.

3. Sustainable Vegetable Cultivation

The demand for high-quality vegetables is growing globally, driven by increasing consumer awareness of nutrition and health [9]. At the same time, vegetable production faces challenges such as labor shortages, rising input costs, and environmental concerns [10]. The study on mulched ridge cultivation systems for solanaceous vegetables highlights how innovative planting techniques and mechanization address these challenges (Contribution 3).

3.1. The Benefits of Mulched Ridge Cultivation

The study on mulched ridge cultivation combined with double-row planting systems revealed multiple benefits, as follows:

Yield improvement: the system increased fresh fruit yields by 40.8% for eggplant and 35.3% for capsicum, demonstrating its potential to enhance food production.

Water conservation: by reducing evaporation and improving soil moisture retention, mulched ridge cultivation is considered a sustainable water management practice, which reduces irrigation water use by up to 32%.

Mechanized planting: the use of advanced transplanters ensures uniform planting depth and spacing, reducing labor requirements and improving planting efficiency.

The study also highlights the role of mechanization in modern agriculture. The newly designed vegetable transplanter integrates multiple functions, including ridging, mulching, and transplanting, in a single pass. This innovation not only reduces labor costs but also ensures consistency in planting, which is critical for optimizing crop performance.

3.2. Addressing Challenges and Opportunities

This research underscores the importance of mechanization in modern agriculture, particularly in regions facing labor shortages or rising costs. Despite its benefits, the adoption of mulched ridge cultivation systems may be limited by factors such as the cost of equipment and the availability of skilled operators [11]. The successful implementation of such systems requires addressing barriers such as high initial costs, the need for operator training, and the compatibility of equipment with diverse farming conditions. Future studies should explore the scalability of these technologies and their integration with precision agriculture tools [12]. To address these challenges, governments and agricultural organizations should invest in training programs and financial support for farmers. Additionally, future research should explore the use of biodegradable mulching materials to mitigate the environmental impact of plastic residues [13].

4. Plastic Mulching and Fertilization for Dryland Crops

Dryland agriculture is particularly vulnerable to water scarcity and soil degradation, making it essential to adopt practices that optimize resource use [14]. The study on plastic mulching and fertilization for tartary buckwheat cultivation demonstrates how these practices improve soil hydration, nutrient efficiency, and crop yields in Northwest China (Contribution 4).

4.1. Optimizing Resource Use in Semiarid Regions

Plastic mulching combined with optimized fertilization offers a powerful tool for improving agricultural productivity in semiarid regions [15]. The study on tartary buckwheat cultivation demonstrates how these practices enhance soil water retention, extend the crop growth period, and boost yields. The study reveals that plastic mulching, combined with low fertilization rates, offers several advantages:

Enhanced soil hydration: Plastic mulching reduced soil evaporation by 22% and increased soil water storage by 19%, allowing crops to thrive even in low-rainfall conditions. It improves water availability for crops by promoting soil water absorption from deep root zones.

Improved nutrient use efficiency: The combination of mulching and fertilization optimized nutrient uptake, resulting in higher grain yields and better grain quality.

Environmental sustainability: While plastic mulching offers agronomic benefits, the study emphasizes the importance of managing plastic residues to minimize environmental risks, emphasizing the need for biodegradable mulching materials.

4.2. Toward Sustainable Dryland Farming

To further enhance the sustainability of dryland farming, future research should focus on developing biodegradable mulching materials and integrating mulching with other conservation practices, such as crop rotation and cover cropping. Policymakers should also prioritize investments in infrastructure and training to support the adoption of these

practices. As plastic mulching gains popularity, it is essential to address its environmental impact through the development of eco-friendly alternatives. Research into biodegradable mulching films and integrated waste management systems will be critical for ensuring the sustainability of this practice.

5. Intercropping Systems and Resource Utilization

Intercropping systems offer a sustainable approach to improving land productivity and resource efficiency [16]. The study on jujube–cotton intercropping systems highlights how reasonable row configurations optimize light capture and reduce competition between crops (Contribution 5).

5.1. Enhancing Photosynthetic Efficiency

The study on jujube–cotton intercropping systems highlights the potential of agroforestry to optimize resource use and improve land productivity. By strategically configuring crop rows, the study demonstrates how intercropping balances competition and complementarity between crops.

Maximized photosynthetic efficiency: Optimized row spacing minimizes competition for water and nutrients between crops, resulting in higher yields. In this study, a four-row cotton configuration was shown to optimize light capture and photosynthetic activity, leading to higher resource utilization efficiency.

Efficient resource allocation: Intercropping reduced competition for light and nutrients between crops, improving overall system efficiency. The configuration ensures that both jujube and cotton plants receive adequate sunlight, enhancing photosynthetic activity.

Sustainability benefits: The land equivalent ratio indicated that intercropping was more productive than monoculture systems, contributing to sustainable land use.

5.2. Toward Sustainable Agroforestry Practices

Intercropping systems have the potential to address several challenges, including land degradation, biodiversity loss, and climate resilience [17]. However, their adoption requires careful planning and coordination, as well as support from agricultural extension services [18]. Future research should focus on developing region-specific intercropping models and evaluating their long-term impacts on soil health and ecosystem services [19].

6. Phosphorus Fertilization and Crop Quality

Phosphorus is a key nutrient for plant growth, but its management poses challenges due to its limited availability and environmental impacts [20]. The study on lentil seed development explores how phosphorus fertilization influences gene expression and seed quality, providing valuable insights for precision nutrient management (Contribution 6).

6.1. Balancing Nutrient Management and Crop Quality

Phosphorus is a critical nutrient for plant growth, and its management has significant implications for crop quality and environmental sustainability [21]. The study on lentil seed development explores how phosphorus fertilization influences gene expression and seed quality. The authors' key findings are as follows:

Gene expression modulation: phosphorus levels affected the expression of genes involved in tannin biosynthesis, impacting seed coat hardness and nutritional value.

Differential effects across stages: the study revealed that phosphorus availability had varying effects at different stages, highlighting the need for stage-specific nutrient management.

6.2. Implications for Sustainable Farming

This research underscores the importance of precision nutrient management in optimizing crop quality while minimizing environmental impacts [22]. By leveraging soil testing and real-time monitoring technologies, farmers can tailor phosphorus applications to meet crop needs more effectively [23]. These findings highlight the significance of precision agriculture tools, such as soil nutrient mapping, in optimizing fertilization strategies, which can reduce environmental impacts while maintaining high crop quality.

7. Alleviating Abiotic Stress in Crops

Abiotic stresses, such as drought, salinity, and nutrient imbalances, are among the greatest threats to agricultural productivity, particularly in the context of climate change [24]. The two studies offer valuable insights into biochemical and hormonal interventions to mitigate abiotic stresses (Contributions 7 and 8).

7.1. Mitigating Calcium Nitrate Stress in Chinese Flowering Cabbage

Excessive calcium nitrate in soil is a common issue in intensive agricultural systems, leading to oxidative stress, disrupted photosynthesis, and reduced yields [25]. The study on Chinese flowering cabbage demonstrates how fulvic acid (FA), a plant growth regulator derived from humic substances, alleviates calcium nitrate ($Ca(NO_3)_2$) stress in cabbage seedlings (Contribution 7). This study underscores the potential of FA as a sustainable and cost-effective solution to mitigate nutrient toxicity in high-intensity farming systems:

Fulvic acid (FA) in Chinese Flowering Cabbage: the application of fulvic acid improved photosynthetic capacity and antioxidant activity, alleviating the effects of calcium nitrate stress.

Exogenous ABA in *Sophora viciifolia*: the use of abscisic acid (ABA) enhanced germination rates and antioxidant enzyme activities, improving drought tolerance.

Photosynthetic recovery: FA restored the photosynthetic capacity of stressed plants by enhancing net photosynthesis, stomatal conductance, and transpiration rates.

Oxidative stress reduction: FA significantly reduced the accumulation of reactive oxygen species (ROS) such as hydrogen peroxide (H_2O_2) and superoxide radicals (O_2^-), as well as malondialdehyde (MDA), a marker of lipid peroxidation.

Antioxidant enzyme activity: the application of FA increased the activity of key antioxidant enzymes, including superoxide dismutase (SOD), catalase (CAT), and peroxidase (POD), thereby enhancing the plant's stress resilience.

Nitrate regulation: FA modulated the expression of nitrate transporters (BcNRT1.1 and BcNRT1.5), limiting nitrate accumulation in shoot tissues and improving nutrient balance.

7.2. Enhancing Drought Tolerance in Sophora viciifolia

Drought stress is a major constraint on plant growth and productivity, particularly in arid and semiarid regions [26]. The study on *Sophora viciifolia* seedlings investigates the role of exogenous ABA in improving drought tolerance (Contribution 8). Key findings include the following:

Improved germination rates: ABA enhanced the germination rate, potential, and index under drought conditions simulated by polyethylene glycol (PEG).

Enhanced antioxidant defense: ABA increased the activities of antioxidant enzymes (POD, SOD, and CAT), reducing oxidative damage caused by drought-induced ROS.

Proline accumulation: ABA promoted the accumulation of proline, an osmoprotectant that helps maintain cellular osmotic balance under water-deficit conditions.

Optimal concentration: the study identified 50 mg L^{-1} ABA as the most effective concentration for enhancing drought resistance, balancing germination performance and stress tolerance.

8. Renewable Energy from Agricultural By-Products

Agricultural by-products, such as grape pomace and distillation stillage, represent untapped resources with significant potential for renewable energy production [27]. The study on biomass pellet production explores how these by-products are transformed into sustainable energy sources, contributing to circular economy goals (Contribution 9).

8.1. The Energy Potential of Grape Pomace and Distillation Stillage

Grape pomace, a by-product of wine production, and distillation stillage, a by-product of brandy production, are rich in organic matter and have high calorific values [28]. The conversion of agro-industrial by-products into renewable energy sources represents a promising avenue for sustainable development. The study on biomass pellet production from wine by-products showcases the potential of grape pomace and distillation stillage as energy-rich materials:

High energy content: distillation stillage exhibited a higher low heating value (>19 MJ kg^{-1}) than grape pomace, making it a viable candidate for biomass energy production.

Chemical composition: while both by-products have high volatile matter content, distillation stillage showed lower ash content and higher fixed carbon, contributing to its superior combustion properties.

Environmental challenges: both materials exceeded ENplus® standards for ash, nitrogen, and sulfur content, necessitating pre-treatment strategies to reduce pollutant levels and improve combustion efficiency.

8.2. Toward Sustainable Energy Solutions

This study underscores the importance of integrating waste management and renewable energy production into agricultural systems, highlighting the dual benefits of reducing agro-industrial waste and generating renewable energy. By closing resource loops, these practices contribute to a more sustainable and circular economy. However, addressing the environmental challenges associated with high pollutant content is critical. Future research should focus on (I) developing pre-treatment technologies, such as washing and torrefaction, to reduce ash and sulfur content in biomass pellets; (II) exploring the co-combustion of grape pomace and distillation stillage with cleaner biomass materials to achieve compliance with energy standards; and (III) scaling up biomass pellet production to integrate renewable energy into local farming and agro-industrial systems.

9. Genetic and Metabolic Diversity in Legumes

Genetic diversity is the foundation of crop improvement, providing the raw material for breeding programs aimed at increasing yield, resilience, and quality [29]. The study on *Vicia sativa* genotypes investigates phenotypic, genetic, and metabolite variability, offering valuable insights for legume breeding (Contribution 10).

9.1. Marker-Assisted Breeding for Common Vetch

Key contributions of the study are as follows:

Genetic diversity assessment: Using start codon-targeted (SCoT) markers, the study identified high levels of genetic polymorphism among four advanced lines and two commercial varieties of *Vicia sativa*.

Metabolomics integration: The metabolomic analysis revealed significant differences in seed composition, linking specific metabolites to yield and biomass traits. Key metabolites, such as fatty acids and amino acids, were identified as potential biomarkers for breeding.

Marker–trait associations: Stepwise multiple regression analysis (MRA) identified SCoT marker bands associated with seed quality traits, providing a basis for marker-assisted selection.

9.2. Implications for Legume Improvement

The integration of genetic and metabolomic data represents a powerful approach to accelerate legume breeding. Future research should focus on (I) expanding the study to include a wider range of *Vicia* genotypes and environmental conditions; (II) validating marker–trait associations in independent breeding populations; and (III) exploring the potential of metabolomics to identify stress-resilient genotypes.

10. Seed Biotechnologies for Sustainable Agriculture

Seeds are the cornerstone of agriculture, and their quality directly impacts crop productivity and resilience [30]. The comprehensive review on seed biotechnologies provides a detailed overview of recent advancements in the past decade (2014–2024), including synthetic seed production, seed priming, and nano-enabled treatments (Contribution 11).

10.1. Innovations in Seed Technology

Key advancements highlighted in the review are as follows:

Synthetic seeds: Encapsulation technologies enable the propagation of elite plant varieties, ensuring genetic uniformity and long-term storage. Synthetic seeds also facilitate the conservation of rare and endangered plant species.

Nano-enabled priming: Nanoparticles enhance seed germination, vigor, and stress tolerance, offering eco-friendly solutions for sustainable agriculture. For example, multi-walled carbon nanotubes (MWCNTs) improve water uptake and germination rates.

CRISPR and genome editing: Advanced genetic tools are being used to enhance seed traits, such as pest resistance, nutrient content, and shelf life, addressing key challenges in modern agriculture.

10.2. Toward Sustainable Seed Systems

These innovations have far-reaching implications for global food security and sustainability. However, their adoption requires addressing challenges such as regulatory approval, farmer access, and public perception. Future research should focus on (I) scaling up synthetic seed production for commercial crops; (II) investigating the long-term environmental impacts of nano-enabled seed treatments; and (III) developing region-specific seed systems that integrate traditional knowledge with modern biotechnologies.

11. Discussion

A summary of the published literature in this Special Issue reveals that remarkable progress has been made across multiple domains of agricultural research and biotechnology, offering innovative solutions to address global challenges in food production [31]. Among these advancements, the integration of precision irrigation technologies shows promise in addressing water scarcity while maintaining crop productivity [32]. Similarly, the adoption of mulched ridge cultivation and intercropping systems is shown to enhance resource use efficiency and yields [33]. In addition, remarkable advancements in phosphorus fertilization, genetic–metabolic diversity, and abiotic stress mitigation provide a robust foundation for developing climate-resilient agricultural systems [34]. In

particular, the conversion of agricultural by-products into renewable energy sources is an excellent example of circular economy development. This represents a significant step toward sustainable agriculture that not only produces food but also contributes to energy security and waste reduction [35]. Additionally, the evolution of seed biotechnologies, including synthetic seed production and nano-enabled treatments, offers promising tools for improving crop quality and resilience [36].

However, several critical challenges must be addressed prior to the successful implementation of these innovations [37]. Making these technologies accessible to farmers across different socioeconomic contexts remains a significant obstacle that requires targeted policy interventions and financial support mechanisms [38]. The effective integration of various technologies and practices requires careful consideration of local conditions, farmer capabilities, and existing agricultural systems [39]. Environmental sustainability is another factor that should be considered. While advancing agricultural productivity, it is crucial to ensure that new technologies and practices contribute positively to environmental conservation and climate change mitigation [40]. This necessitates research on the effect of new bio-technologies on plant growth and quality, soil pollution, and greenhouse gas emissions [41].

Efforts should focus on scaling up proven technologies, such as micro-sprinkling systems, mulched ridge cultivation, and biomass energy production, to benefit farmers worldwide [42]. In the future, continued investment is needed in bio-technological research and development to generate new solutions [43]. Strong policy frameworks that support the adoption of sustainable agricultural practices should be made to enhance the collaboration between researchers and policymakers [44]. New knowledge and technologies should be transferred to industry stakeholders and farmers to enhance resource use efficiency and crop productivity [45]. Governments and international organizations must create enabling environments through subsidies, training programs, and infrastructure investments [46]. As for climate resilience, strategies such as drought-tolerant crops, stress-mitigating treatments, and intercropping systems are needed to make agricultural production adapt to climate change. To reduce the environmental footprint of the agricultural sector, renewable energy applications and eco-friendly farming practices should be aligned with global sustainability goals [47]. It is believed that, by adopting the strategies proposed by the articles published in this Special Issue, we can pave the way for a more sustainable, resilient, and equitable agricultural future (Figure 1).

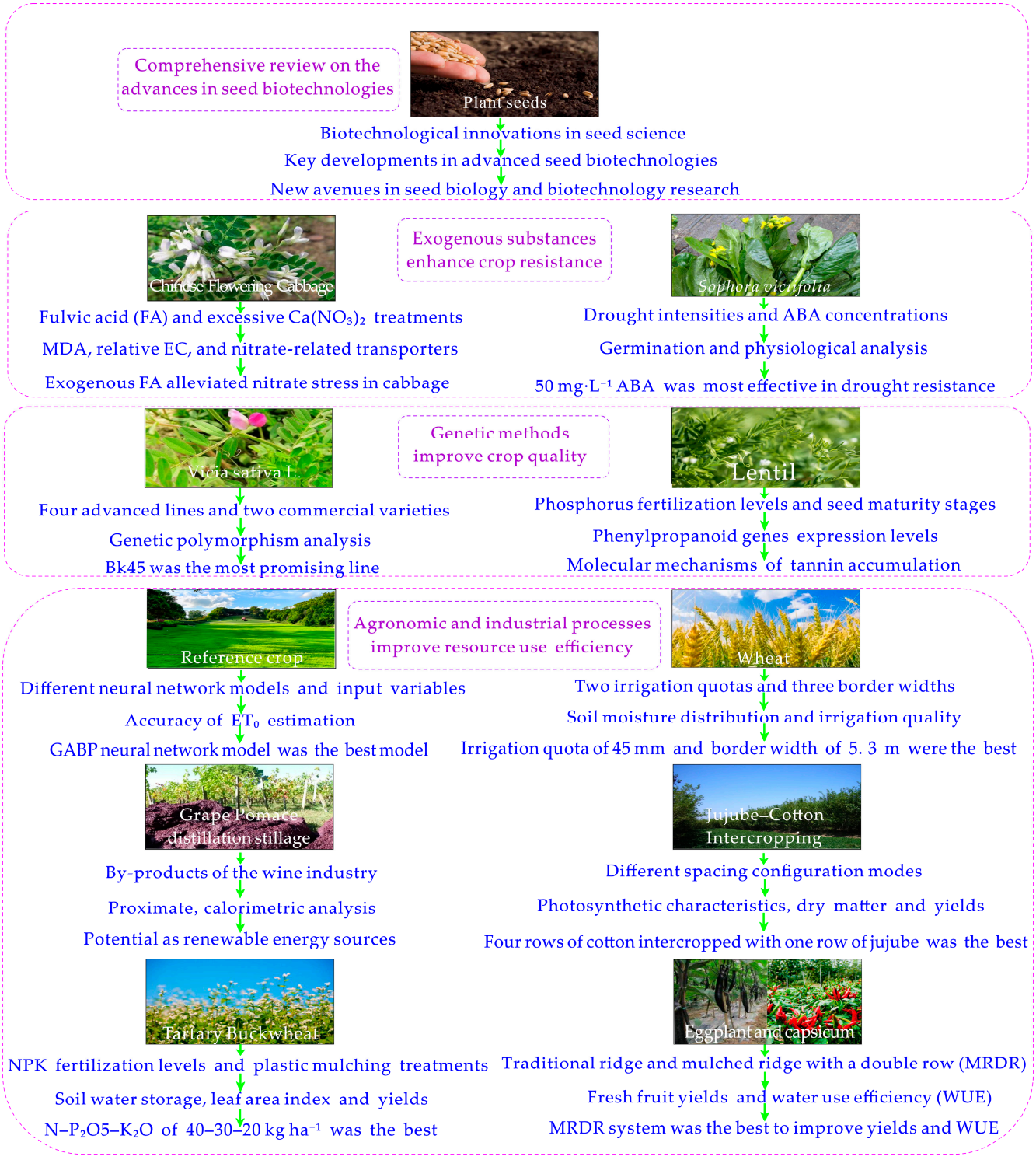

Figure 1. A brief summary and flow chart for the research topics discussed in the Special Issue.

12. Conclusions

The findings presented in this editorial provide a strong foundation for future biotechnological research and development aimed at building a more resilient and sustainable agricultural system capable of addressing the future challenges. The convergence of traditional agricultural wisdom with modern biotechnological advances, coupled with a commitment to sustainability and innovation, offers hope for addressing global food security challenges while preserving natural resources for future generations. In conclusion, while significant progress has been made in developing solutions for sustainable agricul-

ture, the successful transformation of global food systems will depend on our ability to scale these innovations while ensuring their accessibility, sustainability, and adaptability to local contexts.

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