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Review

Research Progress on Water–Fertilizer Coupling and Crop Quality Improvement and Its Implication for the Karst Rock Desertification Control

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Abstract: An important problem currently faced by karst rocky desertification management is the degradation of vegetation fruits, which encourages the search for a solution for the sustainable growth of vegetation. Water and fertilizer are key factors affecting crop quality (the formation of soluble solids, protein, amino acids, soluble sugar content, etc.). A comprehensive review of research related to water–fertilizer coupling and crop quality improvement may be beneficial for rocky desertification control. This study analyzed 427 related papers, and the results showed that: (1) the number of published papers showed an "S" curve growth trend over time, indicating that research in the field of water–fertilizer coupling has entered a mature stage after rapid growth, yet it is still in the initial stage in karst areas; (2) the research was mainly theoretical, but also included technology research and development, model construction, demonstration and extension, and monitoring and evaluation; (3) except for research related to greenhouse facilities, the research areas are mainly located in arid and semi-arid regions. The study further revealed (4) the frontier theory of water–fertilizer coupling and crop quality research. Finally, it was found that the theoretical and technical studies related to water–fertilizer coupling and crop quality improvement in karst areas are insufficient. Whether the existing theories and techniques are applicable to karst areas needs further verification. In addition to the areas of selecting germplasm with high water/fertilizer utilization efficiency and tolerance to rocky desertification, further improvement in the dynamic model of water–fertilizer coupling and the construction of a more applicable water–fertilizer coupling model could also be future research hotspots.

Keywords: water–fertilizer coupling; crop quality; research progress; rocky desertification control; vegetation degradation

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1. Introduction

Water and fertilizer, as critical factors affecting crop growth, development, yield and quality, are flexibly controlled by human beings [1–4]. There is an obvious coupling effect of water and fertilizer [5]. Water is a medium for nutrient transport, and the appropriate amount of water can promote fertilizer conversion and uptake, thus improving fertilizer utilization efficiency, while drought limits nutrient uptake by crops [6]. Fertilizer is the key to improving the productivity of the soil and water systems, and the appropriate amount of fertilizer application can effectively regulate the water usage [7,8]. Improper use of water and fertilizer not only results in the waste of resources and ecological pollution, but also limits agricultural productivity [9–11]. Therefore, water and fertilizer, as they help to increase yield, will show great significance for world food security and sustainable agricultural development.

The karst area in the south of China, with Guizhou Plateau as the center, is the largest and most concentrated karst ecological vulnerable region in the world, with an area of more than 55×10^4 km^2 [12]. Typical karst development brings the most complex and richest landscape types to this region. Due to the distribution of carbonate rocks, the imbalance of hydrothermal conditions under the influence of the monsoon climate, and intensive human activities, the region has significant ecological vulnerability [13–15]. Under the influence of natural and human factors (logging, excessive tillage, grazing, etc.), the karst ecosystem has been degraded, with reduced biodiversity, low productivity of agricultural systems and severe soil erosion, limiting the rapid economic development of the karst region [16,17]. Thus, rocky desertification is the most serious eco-environmental problem in this area, and it is also the main task and difficulty encountered in the process of vulnerable ecological restoration [18]. The construction of sustainable and healthy ecological industries can slow down soil erosion and promote ecological recovery and economic growth in karstic rock desertification areas [12,19,20]. Over the past years, through the efforts of scientists, the recovery of vegetation has been initiated through the plantation of selected crops with high adaptability and resistance in the area, such as pepper (*Zanthoxylum bungeanum* M.), Roxburgh rose (*Rosa roxburghii* T.), pitaya (*Hylocereus undatus* B.), loquat (*Eribotrya japonica* L.), plum (*Prunus salicina* L.) and other economic species.

However, due to barrenness, soil erosion and the uneven spatial and temporal distribution of rainfall [21–23], coupled with the lack of relevant water and fertilizer management technology and people blindly engaged in farming operations, the growth and development of plants are highly susceptible to the influence of water and fertilizer, resulting in early decline, reduced yields and inferior fruit quality in economic fruit plantations, which seriously hinder the healthy economic development in karst rocky desertification areas. Therefore, a review clarifying the status of current research on crop-water–fertilizer coupling and quality improvement can provide a theoretical basis for the scientific management of water and fertilizer and the formulation of sustainable development strategies, thus increasing the income of local inhabitants and the productivity of karst rocky desertification areas.

2. Literature Acquisition and Validation

The foreign literature accessed by the time of the 27 July 2021 was mainly retrieved from Web of Science (http://www.webofknowledge.com, accessed on 27 July 2021), Springer Link (http://link.Springer.com, accessed on 27 July 2021) and Google Scholar (http://scholar.google.com, accessed on 27 July 2021), and the Chinese literature accessed by the same date was mainly acquired from CNKI (http://www.cnki.net, accessed on 27 July 2021), the information resource of China Knowledge Network. The terms used in search engine were: "coupling of water and fertilizer" and "quality." The searching time was set from 1 January 1980 to 31 December 2020. A total of 861 articles were acquired, of which 427 were screened for bibliometric analysis and 115 were cited in this paper.

2.1. Annual Distribution of Literature

A statistical analysis of the temporal distribution of the literature (Figure 1) gives us sense of studies related to water and fertilizer application in the karst rocky desertification areas, as demonstrated in the management of loquat (*Eribotrya japonica* L.), plum (*Prunus salicina* L.), pitaya (*Hylocereus undatus* B.), and pepper (*Zanthoxylum bungeanum* M.) plantations. From 1993 to 2020, the number of relevant literature generally showed an "S" curve growth trend. From 2003 to 2004, there were only six papers reporting on the relationship between water–fertilizer coupling and crop quality, while fewer studies on water–fertilizer coupling and crop quality in karstic desertification areas have been reported. The research mainly covers the effects of water–fertilizer coupling on crop growth and development, yield and its yield components, crop quality, photosynthetic characteristics, soil environment and the efficiency of crop uptake and usage of water and fertilizer. The number of studies has climbed recently, with more than 35 publications per year since 2014. The theory of water–fertilizer coupling has matured with the establishment of the water–fertilizer coupling model for major crops. Researchers have switched their focus to fertilizer efficiency enhancement for various crops. Over the past years, the creation of research material, the improvement of research methods and the advancement of research topics have facilitated water and fertilizer research, discovering an optimized water/fertilizer ratio and irrigation techniques. However, the scarcity of water and fertilizer in vulnerable karst rocky desertification regions means that the optimization of water–fertilizer coupling remains a challenge.

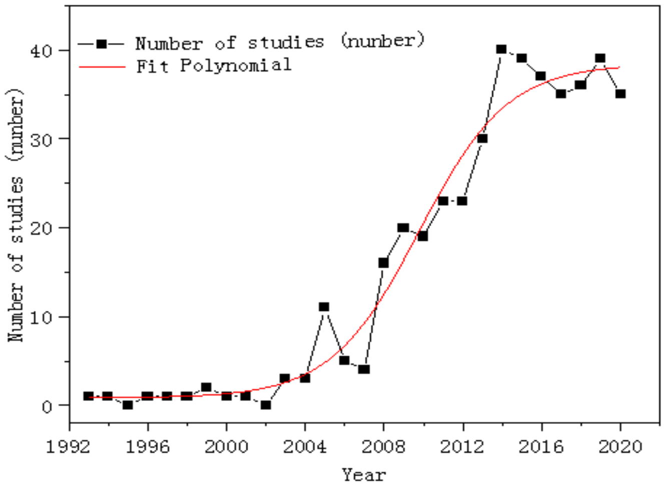

Figure 1. Distribution of water and fertilizer coupling and quality improvement in the literature by year.

2.2. Distribution of Literature Levels and Subject Areas

The literature on water–fertilizer coupling and crop quality was divided into five categories according to the research direction, including theoretical research, technological research and development, monitoring and evaluation, model construction, and experimental demonstration (Figure 2A). Theoretical research accounts for 57% of the total literature, which is the main part of the research; followed by technological research and development, which accounts for 15% of the total; in third place is model construction, which accounts for 11% of the total; experimental demonstration, monitoring and evaluation and other research is relatively rare. Categorized by discipline, the relevant studies fell into eight categories (Figure 2B): horticulture, crops, agricultural engineering, agronomy, basic agricultural science, geography and mapping, forestry and others. Horticulture-related studies account for about 43% of the total research, crops account for 33%, agricultural engineering, agronomy, basic agricultural science, physical geography and mapping and forestry account for less than 5%, and other studies account for 10%. It can be seen that the current research content of related fields involves less natural geography, and is mostly fundamental research and applied fundamental research. It is urgent for us to further broaden the disciplinary field and deepen the research level in the future.

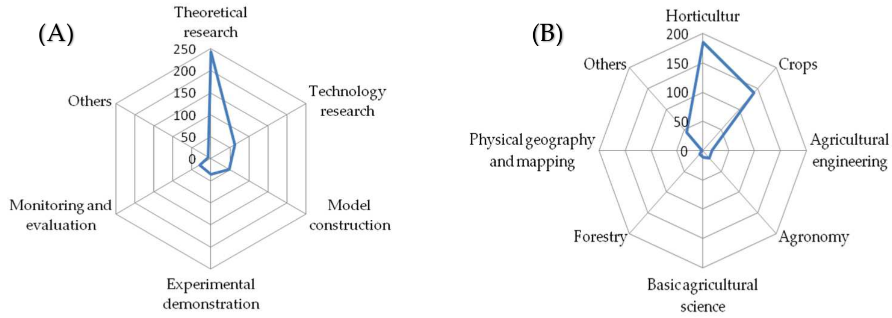

Figure 2. Distribution of literature levels (**A**) and subject areas (**B**).

2.3. Distribution of Research Institutions in the Literature

The distribution of institutions studying water–fertilizer coupling and crop quality was statistically analyzed and summarized (Figure 3A), showing increased interest from universities and research institutes in this field. The top Chinese institutions (Figure 3B) in terms of the number of studies include Northwest Agriculture and Forestry University, Ningxia University, Gansu Agricultural University, Xinjiang Agricultural University, Henan Agricultural University and China Agricultural University. The top English-language institutions (Figure 3C) include the University of Florida, United States Department of Agriculture—Agricultural Research Service, Oregon State University, the University of Tehran and Agriculture and Agri-Food Canada. Most of the research institutions with a high number of publications are agricultural and forestry universities and agricultural research institutes.

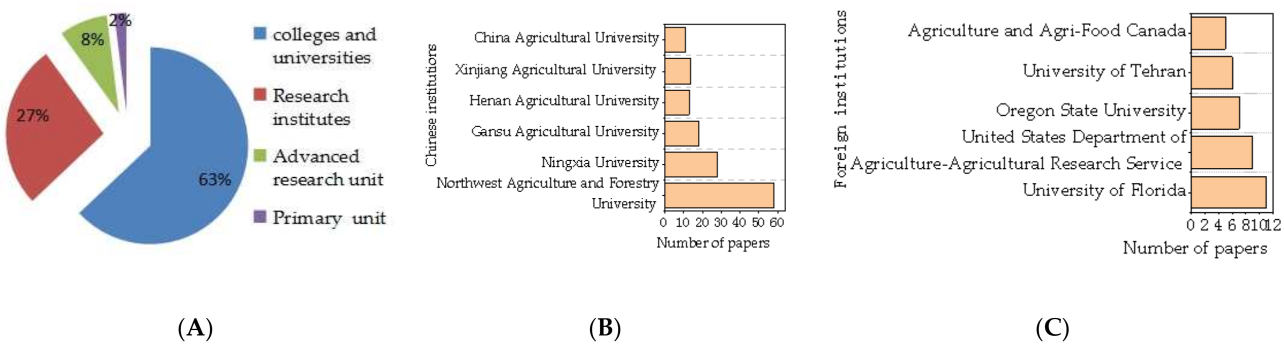

Figure 3. Distribution of research institutions (**A**), (**B**) Chinese institutions and (**C**) foreign institutions.

2.4. Classification of Research Phases

An analysis of the literature on water–fertilizer coupling and crop quality shows that the course of relevant research can be divided into three stages (Table 1). The first stage was from 1993 to 2004, when water–fertilizer coupling and crop quality was in its infancy, with little research literature and few published studies on this topic in karst areas; the second stage was from 2005 to 2014, a period of rapid growth and development; and the third stage was from 2015 to the present, a period of stable development with the improvement of science and technology. The research on water–fertilizer coupling and crop quality improvement has tended to mature, but not in the area of the karst rocky desertification, where the guidance of scientific fertilizer application can no longer be delayed.

Table 1. Research stage.

Stage of Research	Main Characteristics	Background
Embryonic stage (1993–2004)	Less than 5 articles per year, and only 2 articles in the 10-year period of 1993–2002, and only 6 articles related to water–fertilizer coupling and crop quality in 2003–2004, while fewer studies on water–fertilizer coupling and crop quality in karst rocky desertification areas being reported.	At the early stage of reform and opening up, the economic base was weak, traditional agriculture was the mainstay, and scientific research was flourishing slowly.
Rapid development period (2005–2014)	Relevant literature was published every year at home and abroad, and the overall development was rapid; research mainly included the relationship between water and fertilizer coupling and crop quality, spatial and temporal changes in water and fertilizer coupling, water and fertilizer coupling on crop yield, yield constitutive factors, photosynthetic characteristics, soil environment, and crop uptake and utilization efficiency of water and fertilizer.	Although water and fertilizer are important factors in crop growth and development, the negative impact of resource waste and environmental pollution caused by blind fertilization and irrigation cannot be mended by the yield growth. Therefore, water–fertilizer coupling on crop growth, yield and water–fertilizer usage efficiency has become the research focus.
Mature stage (2015 to 2020)	The number of publications surged, with more than 35 papers published each year. The theory of water–fertilizer coupling matured with the establishment of the water–fertilizer coupling model for major crops. Researchers have focused their attention on fertilizer efficiency enhancement for various crops. Over the past years, the creation of research material, the improvement of research methods and the advancement of research topics have facilitated water and fertilizer research, discovering an optimized water/fertilizer ratio and irrigation techniques. However, the scarcity of water and fertilizer in vulnerable karst rocky desertification region still makes the optimization of water–fertilizer coupling a challenge.	Sustainable agricultural development is also listed as an objective of the Food and Agriculture Organization of the United Nations, and more and more researchers are focusing on global issues such as agri-environment, crop quality and food safety. Achieving higher economic and quality benefits with less water and fertilizer usage is a current research goal for scientists. Especially in karst rocky desertification areas, the development of water–fertilizer coupling and crop quality improvement techniques is an urgent scientific research need.

3. Main Developments and Landmark Achievements

3.1. Basic Theory of Water–Fertilizer Coupling and Crop Quality

3.1.1. In Order to Clarify the Relationship between Water–Fertilizer Coupling and Crop Quality, the Theories and Methods from the Disciplines of Plant Nutrition and Fertilizer, Crop Cultivation and Plant Physiology Were Applied to Lay the Theoretical Foundation for the Research on Water–Fertilizer Coupling and Quality

Water and fertilizer regulation during crop growth involves the fundamental theories of plant nutrition and fertilizer, crop cultivation, plant physiology and other disciplines. Scientific water and fertilizer management is crucial for agricultural production. Excessive irrigation and fertilizer application in some areas have not only caused ecological and environmental problems such as groundwater over-exploitation and increased agricultural surface source pollution [24,25], but also led to yield and quality reductions in crops. For the purpose of improving crop yield, quality and water and fertilizer usage efficiency, researchers in various fields have carried out much research around the coupling of water and fertilizer [26–28] in searching for the full synergistic power of water–fertilizer coupling, as well as avoiding resource wastage and ecological pollution problems [29,30].

3.1.2. Coordinate the Relationship between Water and Fertilizer Coupling and Crop Field Canopy Structure according to the Source-Library-Flow Theory of Plant Growth, Improve the Photosynthetic Efficiency of the Group Canopy and Establish a Theoretical Basis for Achieving High Yield and Quality

A suitable water and fertilizer allocation can optimize the canopy structure of a crop field and co-ordinate the relationship between source and reservoir flow. Some scientists found that water was the most important factor affecting crop fertility and yield traits. Its significance can be found in plant height and the leaf area index of winter wheat, increasing with the amount of irrigation and fertilizer application [11,31]. The grain filling capacity and yield of winter wheat could be improved by a moderate water deficit and rational fertilization [32,33]. Maize yield increased with increasing irrigation and fertilizer application under certain conditions, and the increment ceased at the maximum limit [34]. The yield of tomato was correlated with the mass of dry matter, leaf water usage efficiency and net photosynthetic rate at different irrigation and fertilizer application levels [35]. Photosynthetic parameters such as the net photosynthetic rate, transpiration rate and stomatal conductance increased in crops when the amount and frequency of irrigation were appropriate [36,37]; drip irrigation promoted the nitrogen uptake of fruit and the total nitrogen and nitrogen harvest index of plants; phosphorus fertilizer reduced nitrogen concentration in stems and leaves; and potassium fertilizer significantly affected plant nitrogen usage [38]. It can be seen that the appropriate allocation of water and fertilizer can effectively coordinate the accumulation and transformation of crop nutrition and promote plant growth.

3.1.3. Stable Isotope Tracing Techniques Based on the Law of Conservation of Matter to Provide a Theoretical Basis for Crop Water–Fertilizer Coupling and Quality Enhancement Research

In the 1970s, the stable nitrogen isotope dilution tracer technique started its service in the study of environmental pollution problems, and made possible many achievements. Later, the improvement of detection technology promoted the use of the stable nitrogen isotope tracing technology in agriculture, life science, and geochemistry [10,39,40]. Nitrogen, as an element relatively active and mobile in soil, can be easily absorbed, utilized and transferred by plants. As one of the three major nutrients for crops, nitrogen has a much higher effect on crop growth and yield than potassium and phosphorus, so the effect of nitrogen application on crop growth, yield and quality is even higher than that of total fertilizer application. Shi et al. [41] studied the source of nitrogen in plants using the atomic percentage superdetermination method of ^{15}N and concluded that the proportion of fertilizer N and soil N among the sources of nitrogen varied with leaf position in a regular manner. Scientists, by using water-saving irrigation and ^{15}N isotope tracing techniques, obtained some results in rice, wheat, grapes, etc., [42–45]. Therefore, the application of stable isotope tracing techniques provides an important theoretical basis for the study of water and fertilizer coupling.

3.2. Research and Development on Water–Fertilizer Coupling and Crop Quality Enhancement Technologies

3.2.1. In Order to Improve the Efficiency of Water and Fertilizer Resource Utilization and Crop Quality, Research on Water and Fertilizer Integration Technology Is Carried Out to Maximize the Benefits of Water and Fertilizer and Achieve Sustainable Agricultural Development

The traditional "big water, big fertilizer" model not only causes the waste of water and fertilizer, but also bottlenecks the improvement of crop yield and quality. Numerous studies have shown that water–fertilizer integration can significantly improve crop yield and quality compared to traditional irrigation and fertilizer application methods [46–51]. Trace irrigation is an emerging underground water-saving drip irrigation technology that uses capillary forces to supply water to the root zone of crops at low flow rates in accordance with the water demand characteristics of plants [35,52,53]. Huang [54], Xing et al. [55], Yang et al. [56] and Wang et al. [57] have studied the appropriate fertilization techniques for high yield and quality in different crops under trace irrigation, which is a technology integrating fertilizer application, improving water and fertilizer usage efficiency and crop yield and quality.

3.2.2. To Reduce Water and Fertilizer Loss, Conservation Tillage Cultivation Techniques Are Used to Improve Soil Quality, Reduce Soil Erosion and Improve Crop Yield and Quality

Less tillage, no-tillage, straw return and mulching are some of the more common conservation tillage cultivation techniques. It has been found that no-till and minimum tillage cause less disturbance to the soil and can increase soil water content and storage. Straw return can provide organic matter to the soil, reduce air pollution and act as a barrier to control salinization in saline soils. Some scholars have found that straw mulching reduces infiltration, increases the water storage capacity of topsoil and the mineralization rate of soil organic carbon during irrigation, retains water and fertilizer in the upper root zone above the straw deposit layer, reduces percolation and fertilizer leaching and improves crop yield and water use efficiency [58–60]. Mulch not only increases soil temperature and tends to accelerate the turnover of nutrients and carbon in the soil to release nutrients for plant uptake [61], but also reduces the leaching of soil nutrients from rainfall during the rainy season, which has the effect of increasing temperature, water and fertilizer retention. In addition to this, Sui et al. [62] have found that bio-composting is a technique that promotes crop growth and development and improves yield, quality and nutrient accumulation. It can be seen that techniques such as straw return, mulching and bio-composting can increase soil temperature, soil organic matter, water and fertilizer retention and facilitate plant growth and development.

3.2.3. Water–Fertilizer Coupling in Combination with Biochar and Bio-Organic Fertilizers Can Remediate Polluted Soil, Reduce Soil Degradation and Improve Crop Yield and Quality

There have been numerous studies showing that partial replacement of chemical fertilizers by organic fertilizers has significant effects in regulating soil microbial community structure and improving soil properties [63,64]. Organic and inorganic fertilizers not only reduce soil weight, increase total porosity, improve soil physical and chemical properties and significantly improve crop yield and quality [65,66], but also significantly increase soil microbial activity, thus regulating soil microbiota and preventing soil-borne diseases [67,68]. Biochar has a porous structure, which can improve the porosity and water-holding capacity of the soil, reduce soil bulk, and can be used as a supplementary material for transporting plant nutrients [69]. Liu [70] found that water–fertilizer coupling with seafoam passivation for remediation of Cd-contaminated soil could enhance the passivation effect of seafoam and reduce the uptake and accumulation of Cd in oilseed rape within a certain range. Drip irrigation and microbial organic fertilizer had a significant coupling effect on soil carbon emissions, mainly through changing soil organic matter content and root biomass, and influencing soil respiration and the crop yield and quality [71,72]. The combination of deficit irrigation and biochar nitrogen supplementation is a feasible way to improve crop yield and water usage efficiency, significantly improving fruit quality [63].

3.3. Building Up the Model of Water and Fertilizer Coupling and Crop Quality Improvement

3.3.1. To Address the Problem of Water Deficit and Fertilizer Management in the Production of Various Crops in Different Regions, Water and Fertilizer Allocation Methods such as Water Nitrogen, Water Phosphorus and Water Potassium Were Studied to Construct Efficient and Diversified Water–Fertilizer Coupling Models

The best water–fertilizer coupling models, mainly water-nitrogen coupling, water-phosphorus coupling and water-nitrogen-phosphorus coupling, etc., were constructed by research scholars according to the characteristics of crop water and fertilizer demand [73,74]. Pan et al. [75] found that water and nitrogen fertilizer have a certain relationship. As long as water supply and nitrogen fertilizer dosage are appropriately configured, they will play a mutually reinforcing role [48,76]. The optimal water and nitrogen allocation conditions were obtained by studying the effect of water and nitrogen dosage on the yield and quality of apple and rice [77–79]. Zhang et al. [80] carried out a simulation of the effect of drip irrigation fertilization strategy on water and nitrogen dynamics and obtained a suitable water and nitrogen model for drip irrigation. Meng [81] and Li et al. [74] studied water N, water P and water K, as well as the yield and quality of crops in arid and semi-arid areas, and obtained a high yield and quality water–fertilizer coupling model. Shen and Li [82] obtained the best N and P application patterns under different moisture conditions. Meng et al. [83] constructed a coupling pattern of rainfall catchment and water–fertilizer for improvements in apple yield and quality. However, these models were obtained under non-karst conditions, and it is unclear whether these findings are applicable in karstic stone desertification areas with thin soils and a soil nutrient imbalance.

3.3.2. Based on the Difference of Water and Fertilizer Utilization among Crops, Build "Water and Fertilizer Efficient Varieties + Planting Layout" Model

The reasonable arrangement of crop varieties and planting layout is an important part of the efficient use of water and fertilizer. By comparing general crops with drought-tolerant crops and irrigating them according to their water requirements, drought-tolerant crops can also grow and develop well [84]. By adopting intercropping, interplanting, crop rotation, mixed cropping and other planting methods to fully utilize light, heat, water and fertilizer resources and reduce the competitive pressure for crop survival, the soil environment can be improved and water resources utilization and farm production efficiency can be enhanced [85–88]. Wei et al. [89] studied the effects of different densities on yield and water use efficiency under the wheat cover sunflower model, and found that appropriately increasing the density of sunflower can simultaneously improve yield and water use efficiency. Ding et al. [90] intercropped border-irrigated wheat with monopoly furrow-irrigated maize in Gansu and achieved higher yield, water use efficiency and economic benefits than using conventional intercropping. These facts indicate that the selection of resistant, high-yielding and high-quality varieties and the optimization of planting structure, together with the study of water and fertilizer allocation, are important for the sustainable development of agriculture.

3.4. Water and Fertilizer Coupling and Quality Improvement Technology Demonstration

Experimental demonstration studies on water–fertilizer coupling have been carried out in agriculture and livestock staggering areas, mountainous areas, karsts and other locations, all of which have increased yield and quality to different degrees. Fang et al. [91] carried out research on and demonstrated key technologies for water and fertilizer coupling and efficient cultivation in mountain tea gardens, which increased the average yield of tea gardens by more than 10% and increased the income of tea farmers by more than 15%. Gao [92] and Yu [93] carried out research on and demonstrated water and fertilizer coupling and quality improvement technology for Roxburgh rose (*Rosa roxburghii* T.) and golden pear (*Pyrus* L.) in a karst rocky desertification area. Su [94] carried out the integration and demonstration of water- and fertilizer-efficient utilization technology for artificial forage in Ordos pastoral area, Inner Mongolia Autonomous Region, China. Wang [95] carried out the integration and demonstration of precise irrigation and fertilization technology under limited water supply conditions. They found that the yield, quality and economic benefits were improved. It can be seen that water–fertilizer coupling technology has been widely used.

3.5. Monitoring and Evaluation of Water–Fertilizer Coupling and Crop Quality

Sensory evaluation, biochemical and statistical analysis were used to monitor and evaluate the crop quality characteristics and to construct a crop quality evaluation index system under coupled water and fertilizer conditions. The establishment of a scientific and reasonable evaluation system is the basis for obtaining the optimal scheme of water–fertilizer coupling. Sensory evaluation indexes mainly include fruit shape, color, aroma, taste and other indicators, which are generally evaluated by visual inspection, nasal smell, oral taste and other sensory evaluation. Biochemical analysis mainly includes protein, vitamins, fat, soluble solids, soluble sugar, volatile aroma substances and other quality indicators. At present, the water–fertilizer interaction effect is usually measured by different statistics [48,96,97]. Multi-Level Fuzzy Comprehensive Evaluation (MFCE) was introduced to construct a water–fertilizer coupling model for cherry tomato [98]. Multiple regression and spatial analysis were used to comprehensively evaluate yield, quality and fertilizer bias productivity and determine the optimal drip irrigation fertilization program for cucumber and dwarf jujube [99–103]. A game-theoretic combination of subjective Analytic Hierarchy Process (AHP) and the objective entropy weighting method was used to determine the final weights of each index, and a comprehensive evaluation based on the coupled gray correlation and TOPSIS model was conducted to obtain the optimal water and fertilizer allocation scheme [59,72,104]. Wang et al. [74] determined the optimal combination of water and fertilizer inputs for multi-objective optimization by least squares and multiple regression analysis. These methods have a certain range of applicability and provide scientific and technical references for the evaluation of water–fertilizer coupling benefits.

However, different analytical methods may lead to different conclusions in the same experiment. Hu et al. [1] found the W_2F_1 treatment had the best overall fruit quality by using the TOPSIS method; the multi-objective optimization method of a genetic algorithm showed that the W_2F_2 treatment achieved the best outcome. It can be seen that the analysis results obtained by a single technique and method are not comprehensive. In practical application, it is necessary to combine various monitoring techniques and comprehensive evaluation methods to evaluate economic, ecological and social benefits more reasonably.

4. Key Scientific and Technological Problems to Be Solved and Prospects

4.1. In Response to the Degradation of the Vegetation of Economic Fruit Forests and Deterioration of Fruit Products in the Process of Vegetation Restoration in Karst Areas, Scientists Have Explored the Degradation Mechanism in Terms of Soil, Vegetation and Biology to Promote the Sustainable Development of Industries Derived from Rocky Desertification Management

Due to the special above-underground dichotomous structure of karst areas, the surface is highly heterogeneous, the proportion of bare rock area is high, soil distribution is discontinuous and underground space caves, fissures and underground rivers are widely spread. Driven by rainfall, soil nutrient loss is serious, which will lead to crop water and nutrient imbalance, affecting yield and quality, if there is a lack of timely water and fertilizer supplementation. In response to the degradation of forest ecosystems, grassland ecosystems and mossy plant ecosystems in karst areas, scientists [100,105–108] have conducted much research on their morphological establishment, photosynthetic physiology, water uptake, nutrient utilization and microecological environment, respectively. A series of research results have been obtained. However, the core factors are still inconclusive, and the role of water and fertilizer factors needs to be further investigated.

4.2. In Order to Solve the Problem of Lag in the Research of Soil Nutrient Limiting Critical Value and Precise Irrigation Thresholds and the Allocation of Water and Fertilizer, It Is Necessary to Analyze Natural and Human Factors, Searching for New Technology Integration Modes from a Multi-Disciplinary Perspective

The nutrient element imbalance in soil, especially in karst rocky desertification regions in China, was mainly due to the unscientific use of fertilizers. The low use of organic fertilizers and the abusive application of nitrogen, phosphorus and potassium has aggravated the nutrient imbalance. The progressive disciplines, such as plant nutrition and fertilizer science, soil science, plant physiology and others, have suggested scientific fertilizer application techniques including "formula fertilization with soil testing" and "precise irrigation." These techniques have taken the limited critical value of the eco-stoichiometry of carbon, nitrogen and phosphorus into account. Ultimately, the continuous study of scientific water and fertilizer usage will push it to the breakthrough point.

4.3. In View of the Influence of Water–Fertilizer Coupling on Crop Quality, It Is Necessary to Determine Water Irrigation and Fertilizer Application Methods Based on Local Conditions, Integrate Appropriate "Water for Fertilizer, Fertilizer for Water Regulation, and Fertilizer-Water Coordination" Technologies, and Explore the Mechanism of Water–Fertilizer Coupling to Provide Scientific and Technological Support for Sustainable Agricultural Development

Some preliminary results about water–fertilizer coupling and crop quality improvement [109–111] have been obtained in different countries, including the United States, India, Australia, Canada and China. Yet similar studies in karst rocky desertification regions are still in their initial stage. The applicability of existing water–fertilizer coupling technology in karst areas with strong heterogeneity and serious water–fertilizer leakage needs to be further verified. The development of an ecological compound industry in karst rocky desertification areas not only drives local economic development, but also helps to improve vegetation coverage, which is critical for rocky desertification management and ecological restoration. Therefore, considering the social, economic and ecological benefits it brings, the water–fertilizer coupling mechanism needs to be further explored, especially in karst rocky desertification areas.

4.4. In View of the Spatial and Temporal Heterogeneity of Water–Fertilizer Coupling, It Is Necessary to Further Improve the Construction of Dynamic Model of Water–Fertilizer Coupling and Explore the Suitable Water–Fertilizer Coupling Mode in Karst Areas from Multiple Fields and Perspectives

In order to improve the plant growth environment and increase fertilizer utilization, water–fertilizer coupling technology has been increasingly applied, regulating the plant irrigation amount, fertilizer application time and method in a manner beneficial to plant growth and development [112,113]. Scientists have carried out much research on the coupling of water and fertilizer for different crops in different ecological environments, and set up a series of water and fertilizer coupling models. However, all of these results have been obtained under certain conditions. The karst rocky desertification environment has a unique binary three-dimensional spatial heterogeneous structure and problems with the serious loss of water and fertilizer, which makes the study of the water–fertilizer coupling mechanism exceptionally difficult. Using variations in space to simulate variations in time is a commonly used method to explore the physiological-ecological characteristics and quality features of crops with different water–fertilizer configuration patterns on the same time scale. It can reflect certain mechanisms, but there are more non-limiting factors, and it is difficult to reveal the continuous migration of crop nutrients with a water source under different water–fertilizer configurations. Therefore, we need to conduct research from a multidimensional perspective.

4.5. To Address the Problems of Uneven Spatial and Temporal Distribution of Large Rainfall, Lack of Water Storage Facilities and Poor Water and Fertilizer Retention Capacity of Soils in Karst Areas, Research on the Water and Fertilizer Requirements of Different Land Types in Karst Rocky Desertification Areas Contribute to the Healthy Development of Agriculture in Karst Areas

Karst rocky desertification areas are typically "counting on the farther sky," and rainfall plays a crucial role in crop production in these areas. Although research on the water–fertilizer coupling of *Rosa roxburghii tratt* and golden pear (*Pyrus* L.) in karstic desertification areas has been carried out by Gao [92] and Yu [93], the soil characteristics of the area, such as its high calcium content and phosphorus deficiency, have been neglected. Therefore, it is necessary to carry out further research on water–fertilizer coupling and quality improvement technology for karst-specific economic fruit forests, increasing the completeness of each link as well as the flexibility of migration, and calibrate model parameters adapting to the characteristics of different areas, so as to construct an applicable water–fertilizer coupling model addressing the vegetation degradation and fruit decline problems.

4.6. To Address the Ecosystem Degradation in Karst Rocky Desertification Areas, in Addition to Optimizing Water and Fertilizer Allocation, Appropriate Screening and Cultivation of Ecological and Economic Crop Varieties with Strong Resistance and Wide Adaptability and High Utilization of Water and Fertilizer Should Be Carried Out

Karst areas have rugged and fragmented surfaces, high mountain slopes, high rates of bedrock exposure, structural deficiencies in water and soil elements, many rocks and few soils, extremely slow soil formation, arid surfaces, shortage of available water and fertilizer resources, fragile ecosystems and low thresholds of resistance to external disturbances [17,114]. Therefore, artificial restoration should be the main focus when conducting vegetation restoration. The suitability, diversity and economy of artificially reconstructed plant species are the main principles [12,16,115] (Wu et al., 2011). It should not only emphasize the restoration of their original state, but also consider the combination of ecological restoration with industrial construction and rural revitalization. To expand the research field to the screening and breeding of highly resistant and widely adaptable crop varieties and the high utilization of water and fertilizer has ecological and economic benefits. This would help meet the new demands of karst rocky desertification control, improve farmers' economic income and contribute to rural revitalization.

5. Conclusions

The improper management of water and fertilizer has caused advanced plant degradation in the process of karst rocky desertification control, which has damaged attempts at ecosystem restoration and sustainable development in the region. In this paper, the relevant water and fertilizer technologies for improving crop quality were reviewed to provide a reference for crop quality improvement in karst areas. The studies on water–fertilizer coupling have started only recently in this area. Most of the theoretical water–fertilizer coupling parameters, as the environmental conditions, are different from other study areas for many reasons, including soil barrenness and lack of water resources in the karst regions, and still await validation. Therefore, it is an urgent scientific and technological problem to research the coupling technology of water and fertilizer suitable for this region.

In future research, we can broaden the research field on the basis of the existing research on water–fertilizer coupling technology, and explore the response mechanism of crop quality to water and fertilizer by combining the soil standing conditions in karst areas. We should construct a suitable water–fertilizer coupling model for economic fruit forests, and clarify the mechanism driving water and nutrient supply for the growth and development of economic fruit forests in karst areas, so as to provide scientific and technological references for vegetation restoration in national and local stone desertification control areas.

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