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Comparative Application of Fertilizer-Water Coupling Management in High-Yield *Camellia* Cultivation across Different Soil Types

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Abstract This study mainly focuses on how *Camellia oleifera* can increase its yield and oil yield through scientific management of fertilizer and water. It summarizes the achievements in the combined use of water and fertilizer in recent years, with a particular emphasis on how nutrients such as nitrogen, phosphorus, and potassium interact with water. It also compares water and fertilizer management methods under different regions, soil conditions, and climatic conditions to see which strategy is the most effective under which conditions. It also summarizes the effective methods currently available in terms of fertilization timing, irrigation frequency and refined operation, and analyzes whether this management approach can be helpful for resource conservation, environmental protection and achieving efficient and green production. This study aims to provide references for *Camellia oleifera* cultivation in various regions and help achieve sustainable development.
Keywords *Camellia oleifera*; Fertilizer-water coupling management; High-yield cultivation; Resource use efficiency; Regional adaptability

1 Introduction

Camellia oleifera is an important oil tree species in China. Its output and the quality of the oil directly affect economic income and ecological protection (Luan et al., 2020; Quan et al., 2022; Yao et al., 2024). But nowadays, many *Camellia oleifera* forests have low yields and poor oil quality. The main problems lie in poor soil fertility and inadequate management. To increase the yield and quality of *Camellia oleifera*, it is necessary to improve the planting methods, especially to conduct meticulous management according to different soil conditions (Chen et al., 2023).

The fertilizer-water coupling technology is to manage fertilization and watering in combination. This method can improve soil conditions, enable *Camellia oleifera* to grow better, and also enhance the utilization efficiency of nutrients (Xing et al., 2024). Components such as soil moisture, pH, nitrogen, phosphorus and iron can all affect the absorption of nutrients and the quality of the fruit of *Camellia oleifera*. If water and fertilizer are properly combined, not only can the roots, leaves and fruits of *Camellia oleifera* better transfer nutrients, but also the yield and oil yield can be increased (Chen et al., 2023; Luo et al., 2024). Nowadays, intelligent management systems have been adopted in some places, which not only improve the utilization rate of water and fertilizer, but also reduce environmental pressure and make agriculture greener.

This study compared the effects of the combination of fertilizer and water on the growth, nutrient absorption, yield and quality of *Camellia oleifera* under different soil types, identified which factors played a key role, and analyzed how they affected *Camellia oleifera*. This study aims to provide a reference for high-yield cultivation of *Camellia oleifera* and also offer technical guidance to growers.

2 Principles of Fertilizer-Water Coupling (FWC) in *Camellia* Cultivation

2.1 Concept and agronomic rationale of fertilizer-water coupling

Fertilizer-water coupling (FWC for short) refers to the practice of using water and fertilizer together during the growth of crops. The timing and proportion are adjusted as needed to help plants grow better and have higher

yields. The principle of this method is that water can help dissolve and absorb fertilizers, and with sufficient nutrients, crops can also use water more effectively. When combined, the two can improve the soil, make plants grow faster and use resources more economically (Xing et al., 2024). Studies have found that the combination of fertilizer and water can improve soil structure, make microorganisms and enzymes in the soil more active, and also reduce fertilizer waste and environmental pollution. It is a green and efficient agricultural method (Xing et al., 2024).

2.2 Physiological responses of *Camellia* to water-nutrient synchrony

The combined response of *Camellia* oil (*Camellia* spp.) to water and nutrients is very obvious. For instance, the combination of water with nitrogen and phosphorus can affect the stem diameter, chlorophyll content and unit leaf weight of seedlings, as well as plant height and photosynthesis. The research also pointed out that if the water content is 55% of the field capacity, and nitrogen is applied at 5.43 grams per plant and phosphorus at 2.40 grams per plant, such a formula can make the *Camellia oleifera* seedlings grow best and the leaves also grow well. However, too much nitrogen can inhibit photosynthesis, and too little nitrogen or phosphorus can also cause poor leaf growth (Luo et al., 2024). On tea plants, nitrogen has the greatest impact on dry matter, followed by water and phosphorus. The combination of these three is also very helpful for increasing yield (Wang et al., 2016).

2.3 Technical approaches: drip fertigation, slow-release fertilizers, and scheduling strategies

In fertilizer and water management, there are three common methods: drip irrigation fertilization, slow-release fertilizers, and intelligent control systems. Drip irrigation fertilization delivers water and fertilizer to the roots of crops through pipes. This method is very accurate and relatively water-saving and fertilized. It is a frequently used approach in agriculture nowadays (Lin, 2024; Xing et al., 2024). The function of slow-release fertilizers is to gradually release nutrients, allowing crops to absorb them as needed. This not only reduces the frequency of fertilization, but also reduces fertilizer loss and is more environmentally friendly (Xing et al., 2024). Nowadays, many places have also adopted Internet of Things (IoT) and big data technologies. Through these tools, one can check the moisture in the soil, weather changes and how the crops are growing at any time. The system can automatically adjust the supply time and quantity of water and fertilizer based on this information, replenishing what is lacking and providing when needed (Figure 1) (Lin, 2024). As these smart devices become increasingly popular, the water and fertilizer utilization efficiency and growth of *Camellia oleifera* can also be improved, and the quality of the fruits is expected to become better. These new methods also provide new directions for the digital and intelligent development of agriculture.

3 Classification and Characteristics of Soil Types in *Camellia*-Producing Regions

3.1 Red soil regions: high acidity, leaching, and clay content

In southern China, *Camellia oleifera* is widely grown on red soil. This kind of soil is slightly acidic (pH is often lower than 6.0), has a lot of clay, and water washes away nutrients relatively quickly. There is not much organic matter in the red soil, the fertility is relatively low, and the trace elements are often uneven (Liu et al., 2018a). When growing *Camellia oleifera* in this kind of soil, special attention should be paid to the problems caused by acidic soil. Adding appropriate organic fertilizer and adjusting pH can help improve the quality and yield of *Camellia oleifera* (Yang et al., 2023; Xu et al., 2023).

3.2 Sandy loam and alluvial soils: drainage and water-holding differences

In addition to red soil, *Camellia oleifera* is also commonly grown in sandy loam and alluvial soil. Sandy loam soil is loose, water drains quickly but is not easy to retain water, and nutrients are also prone to loss. The conditions of alluvial soil are quite different. Its parent materials are diverse, and in some places, its water retention capacity is quite good. However, the fertility is related to its composition and the amount of organic matter (Liu et al., 2018b; Tu et al., 2019). Growing *Camellia oleifera* in these two types of soil requires reasonable water and fertilizer management to maintain the supply of water and nutrients, which is crucial for high yield.

3.3 Rocky-mountain soils and degraded lands: fertility and moisture retention issues

In mountainous areas, some areas are calcareous soil or degraded land. These soils have very shallow layers, poor water retention and few nutrients. Although some *Camellia oleifera* varieties can adapt to calcareous soil, on the

whole they are still not as good as red soil or alluvial soil (Zhu et al., 2022). To grow *Camellia oleifera* well in this kind of land, more organic fertilizer should be applied to improve the soil structure and enhance the water and nutrient retention capacity, so as to ensure the normal growth and high yield of *Camellia oleifera* (Liu et al., 2018b; Liu et al., 2023).

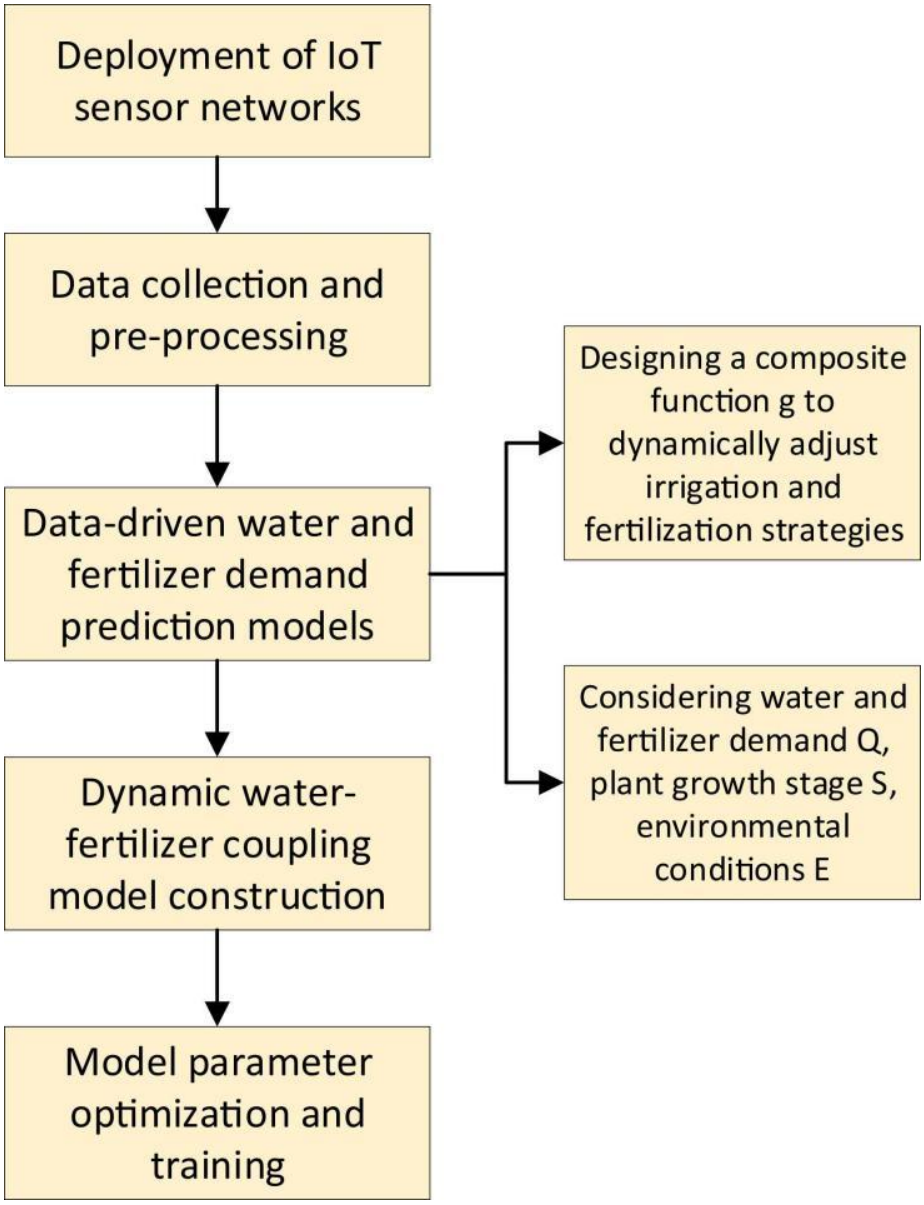

Figure 1 Dynamic water-fertilizer coupling model based on IoT (Adopted from Lin, 2024)

4 Comparative Performance of FWC under Different Soil Types

4.1 Nutrient use efficiency (NUE), water use efficiency (WUE), and plant uptake across soils

A good combination of fertilizer and water can significantly enhance the utilization efficiency of nutrients and water by *Camellia oleifera*. Studies have found that soil pH, moisture, as well as elements such as nitrogen, phosphorus and iron, can affect the absorption and utilization of key nutrients like N, P, K, Cu and Mn by *Camellia oleifera*. These elements sometimes help each other and sometimes influence each other, ultimately determining the yield and oil composition of *Camellia oleifera* (Figure 2) (Chen et al., 2023). For example, in different soils, using an appropriate water-fertilizer ratio (such as 55% field water holding capacity, adding an appropriate amount of nitrogen and phosphorus) can enable *Camellia oleifera* seedlings to grow faster, have more chlorophyll, and have stronger photosynthesis (Luo et al., 2024). The application of intelligent water and fertilizer system can further save water and fertilizer and reduce loss (Xing et al., 2024).

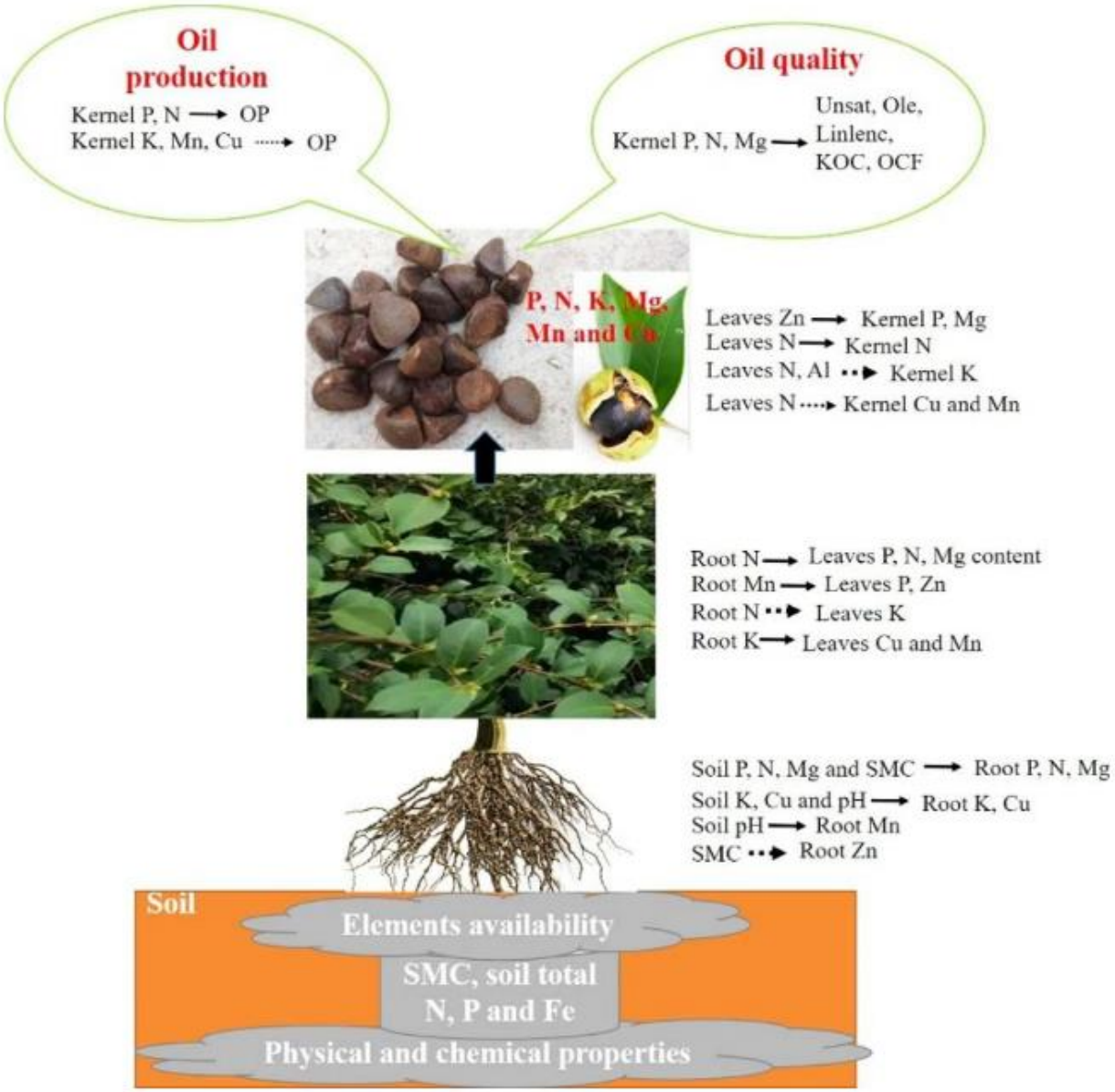

Figure 2 Role of soil nutrient transport on *C. oleifera* yield and quality under different soil types (Adopted from Chen et al., 2023)

4.2 *Camellia* yield response and fruit oil content variation under different conditions

Different soil and water and fertilizer management methods can lead to significant differences in the yield and oil quality of *Camellia oleifera*. For example, if the contents of N, P, Mg and Zn in the leaves are increased, or the soil moisture is maintained appropriately, the oil yield can be higher and the oil quality can be better, especially with more unsaturated fatty acids (Chen et al., 2023). In Hunan, different types of soil require different amounts and proportions of fertilizer application. For instance, for acidic purple soil, a ratio of N:P:K of 3.5:1:3.5 is used. Applying 3.6 kilograms per tree annually can maximize the yield. Furthermore, a good combination of fertilizer and water not only increases the yield but also improves the quality of the oil (Chen et al., 2023).

4.3 Soil improvement feedback: organic matter, pH regulation, and microbial effects

Fertilizer-water coupling management can also improve soil conditions, making the soil structure more stable, with more organic matter and more diverse microbial species. It can also help decompose organic matter and release nutrients (Xing et al., 2024). Adding some organic fertilizers, such as the fertilizer made after the fermentation of *Camellia oleifera* shells, can greatly increase the contents of organic matter, nitrogen, phosphorus, potassium, etc. in the soil, and also make the microbial population healthier (Huang et al., 2023). However, it should be noted that if the *Camellia oleifera* fields are not managed properly for a long time, the soil will become

acidic, nutrients will be exhausted, and the activity of microorganisms will also decline. At this time, it is necessary to regulate through scientific water and fertilizer management methods to restore the vitality of the soil (Zong et al., 2025).

5 Practical Management and Adaptation Strategies

5.1 Tailored fertilization programs for specific soil types

Different soil types will directly affect the nutrient absorption and yield of *Camellia oleifera*. Research indicates that six types of soil, such as acidic purple soil, granite sandy soil, and carbonate red soil, each require different fertilization methods. For instance, for acidic purple soil and granite sandy soil, it is recommended to apply nitrogen, phosphorus and potassium in a ratio of 3.5:1:3.5, with 3.6 kilograms per tree per year. For carbonate red soil, apply a ratio of 3.2:1:3.3, with 3 kilograms per plant per year. If soil tests can be conducted in advance and the fertilization plan is designed in combination with the target yield, the yield and *Camellia oleifera* quality can be improved more scientifically (Chen et al., 2023).

5.2 Water management schemes considering soil texture and retention capacity

The texture of the soil and its water retention capacity also affect irrigation strategies. Generally speaking, keeping the water content within the range of 40% to 70% of the field capacity and combining it with an appropriate amount of nitrogen and phosphorus can help *Camellia oleifera* grow faster and use water more effectively. However, the water retention capacity of different soils varies. For instance, sandy soil is prone to leakage, while alluvial soil retains water better. Therefore, the frequency and amount of irrigation should be adjusted according to the specific conditions of the soil. It should neither be overwatered nor underwatered, otherwise it will cause fertilizer loss or root hypoxia (Chen et al., 2023; Luo et al., 2024; Xing et al., 2024).

5.3 Integration with soil amendments, mulching, and planting patterns

In addition to the water and fertilizer ratio, the application of organic fertilizers is also very important. For instance, organic fertilizers made from *Camellia oleifera* shells, biochar or humic acid fertilizers can all improve soil structure, increase the content of organic matter and nutrients such as nitrogen, phosphorus and potassium, and also increase the variety of microorganisms in the soil. In addition, laying a layer of organic mulch can reduce water evaporation, suppress weeds and also regulate soil temperature. Combined with appropriate planting density and interrow covering measures, it helps the root system to grow better and also increases the yield of *Camellia oleifera* (Sui et al., 2021; Xu et al., 2021; Huang et al., 2023).

6 Case Study: Field Comparison of FWC Models in Contrasting Soil Environments

6.1 Study site selection: soil profiles, climate, and *Camellia* variety used

This case study selected six typical soil types for *Camellia oleifera* cultivation in Hunan Province, including acidic purple soil, shale-derived red soil, carbonate red soil, marl red ash soil, sandstone red soil and granite sand soil. The local area belongs to a warm and humid climate zone, with annual precipitation ranging from 1,000 to 1,980 millimeters and an average annual temperature of 14 ℃ to 16 ℃, which is very suitable for the growth of *Camellia oleifera*. The *Camellia oleifera* varieties used in the experiment were common high-yield varieties in the local area, ensuring the representativeness and comparability of the experimental results (Malyukova et al., 2023).

6.2 Experimental treatments, monitoring methods, and data collected

Each experimental site adopts the soil test results to formulate fertilization and combines water and fertilizer coupling management. Different nitrogen, phosphorus and potassium ratios and irrigation plans have been set for each type of soil. For instance, for acidic purple soil and granite sandy soil, apply N:P:K=3.5:1:3.5, with 3.6 kilograms per tree per year. The ratio of shale-derived red soil is 3:1:3, with 3.2 kilograms per year. The research content included indicators such as soil pH, organic matter, available nitrogen, phosphorus and potassium, and also observed the ground diameter, plant height, chlorophyll content, specific leaf weight, yield and economic benefits of *Camellia oleifera*. Data were collected through regular sampling, field yield measurement and economic analysis, etc. (Luo et al., 2024).

6.3 Results: yield, economic return, and soil parameter changes

The results show that the fertilizer-water coupling management can significantly increase the yield and economic benefits of *Camellia oleifera*. Under different soil conditions, after a reasonable combination of fertilizers and water, the yield could reach 1.5 to 4.8 times that of the control group, and the income also increased significantly (Malyukova et al., 2023). For example, under the conditions of 55% field water holding capacity, 5.43 grams of nitrogen and 2.40 grams of phosphorus per plant, the growth effect of *Camellia oleifera* was the best (Luo et al., 2024). Long-term use of this management approach can also improve soil structure, increase organic matter and available nutrients, make soil pH more suitable for crop growth, and enhance the diversity of soil microorganisms (Sui et al., 2021; Xing et al., 2024). However, if excessive nitrogen is applied, it may also inhibit the photosynthesis of *Camellia oleifera*. Therefore, it is necessary to optimize the water and fertilizer management strategies according to different soil conditions and the growth stage of *Camellia oleifera* (Li et al., 2019).

7 Challenges and Limitations

7.1 Technical constraints in infrastructure and cost for FWC implementation

In practical operation, the fertilizer-water coupling management requires the application of some modern technologies, such as Internet of Things monitoring and automatic irrigation systems. Although these smart devices are highly efficient, both purchasing them and maintaining them later are not cheap, so they are not easy to promote in some areas with poor economic conditions (Lin, 2024; Xing et al., 2024). The traditional management methods often lead to problems such as waste of water and fertilizer or unstable growth of *Camellia oleifera*, which precisely indicates the importance of supporting infrastructure.

7.2 Regional climate-soil mismatches and risk of nutrient leaching

The weather and soil conditions vary greatly in different regions, which makes it difficult to apply a uniform standard to the fertilizer-water coupling management. Conditions such as rainfall, temperature and soil permeability can affect the effectiveness of fertilizers. In some areas, it rains a lot or the soil is loose. Fertilizers are prone to being washed away, which not only affects the yield but may also cause pollution (Malyukova et al., 2023; Xing et al., 2024). In addition, *Camellia oleifera* is highly sensitive to nitrogen fertilizer. Excessive use may instead affect photosynthesis and even cause plant discomfort (Li et al., 2019; Luo et al., 2024).

7.3 Farmer adoption, labor demand, and knowledge gaps

The fertilizer-water coupling management also puts forward new requirements for the technical level of farmers. Some farmers are not yet familiar with these new devices and have not received systematic training. As a result, they may not be able to adjust the ratio of water to fertilizer properly, which will affect the yield and utilization efficiency of crops. Moreover, some intelligent systems are rather complex to operate, and manual management also needs to keep up, which brings certain difficulties to their promotion (Lin, 2024; Xing et al., 2024).

8 Concluding Remarks

Different types of soil can affect the absorption of nutrients, yield and oil quality of *Camellia oleifera* by adjusting moisture, pH value and the content of elements such as nitrogen, phosphorus and iron. Research has found that moisture, pH value, and total nitrogen, total phosphorus, and total iron are the main factors affecting nutrient absorption and yield, while elements such as N, P, K, Cu, and Mn have the greatest impact on seed kernel development and yield. The fertilizer-water coupling management not only enhances the utilization efficiency of these elements, but also improves soil structure, increases the variety of beneficial microorganisms in the soil, boosts enzyme activity, and ultimately promotes the growth and yield increase of crops. Therefore, under different soil conditions, the management of water and fertilizer should be combined with the local soil characteristics and the water and fertilizer requirements of *Camellia oleifera* in order to achieve the goal of high yield and high quality.

When growing *Camellia oleifera*, different sites should adopt different water and fertilizer management plans. If the soil is rich in nutrients and has good water retention, more nitrogen, phosphorus and potassium can be applied appropriately, combined with a moderate amount of irrigation. For relatively infertile or acidic soils, priority should be given to supplementing key nutrients such as nitrogen, phosphorus, magnesium and zinc. At the same

time, foliar spraying or layered fertilization can be adopted to enhance the absorption efficiency of nutrients. In addition, too much nitrogen fertilizer should not be applied, otherwise it is easy to inhibit photosynthesis and lead to poor growth of the plants. It is recommended to adopt low to moderate intensity nitrogen fertilizer management, which is more conducive to balancing the yield and stress resistance of *Camellia oleifera*. Promoting intelligent water and fertilizer integration systems is also a good way to improve efficiency. It can not only reduce waste but also alleviate the pressure on the environment and help achieve the goal of green planting.

From a research perspective, it is necessary to establish a long-term soil and yield monitoring mechanism in the future, continuously observing the impact of the fertilizer-water coupling management on the yield, quality and soil health of *Camellia oleifera* under different soil conditions. This can provide data support for scientific fertilization and irrigation. At the same time, efforts should also be made to promote the development of digital agricultural technologies, such as developing intelligent decision-making systems to make water and fertilizer management more precise and automated. Finally, it is necessary to conduct in-depth research on the interrelationships among *Camellia oleifera*, soil, water and fertilizers, and build a scientific regulatory model to provide theoretical support and operational guidelines for achieving precision agriculture.

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Conflict of Interest Disclosure

The authors affirm that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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