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Optimizing Planting Density and Sowing Date for Mechanized Direct-seeded Rice in Subtropical Regions

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Abstract In subtropical rice-growing areas, the problems of rising labor costs and tight water resources have become increasingly prominent, promoting the rapid development of Mechanized Direct-seeded Rice (MDSR) technology. However, as the key factors affecting the yield and stability of mechanical direct seeding rice, the optimal combination of sowing period and planting density has not yet been systematically studied and precisely guided in subtropical regions. This study aims to clarify the influence mechanisms of different sowing periods and planting densities on the growth and development, population structure, yield composition and resource utilization efficiency of mechanically direct-sown rice in subtropical regions, explore their interaction relationships, and systematically evaluate the physiological and ecological performance of various combinations of sowing periods and densities through field trial cases conducted in South China. Combined with meteorological data and yield factor analysis, efficient and stable production plans were screened out, striving to provide a scientific basis for the regionalized cultivation of mechanical direct seeding rice. This research not only enriches the theoretical system of efficient rice cultivation, but also provides practical support for promoting the regional adaptation of mechanized and intelligent green rice cultivation, which is of great significance for ensuring food security and achieving sustainable agricultural development.
Keywords Rice (*Oryza sativa* L.); Mechanical live streaming; Planting density; Sowing period; Output optimization

1 Introduction

Rice (*Oryza sativa* L.) has always been one of the staple foods in subtropical regions, but in recent years, the difficulty of growing it has been increasing. The labor force is decreasing, water sources are not as stable as before, and the climate is always "throwing a tantrum". The traditional practice of relying on manual transplanting, excessive irrigation and high cost is no longer able to cope with the current situation. Especially against the backdrop of the continuous flow of young labor force to cities and the increasing difficulty in farmland management, the sustainability of this approach is being tested.

To address these issues, many places have begun to experiment with the practice of directly sowing seeds instead of raising seedlings for transplanting - direct seeding rice (DSR). Labor-saving, water-saving, and more resilient in the face of some extreme weather (Jat et al., 2022). However, not all direct seeding rice systems can meet expectations. The mechanized type, especially new technologies such as row seeding and drone broadcasting, currently seem to have more potential for development. Methods like mDSR (Mechanized Direct Seeding Rice) not only help farmers save seeds and fertilizers, but also ensure uniform emergence and are easy to manage. Many studies have also found that its output is comparable to that of traditional methods, and sometimes even higher. Moreover, it has low cost, few diseases, light lodging, and can even significantly reduce greenhouse gas emissions (Wang et al., 2021). From a broader perspective, it meets the demands of green agriculture and is also suitable for coping with extreme climates, improving the utilization rate of nitrogen fertilizers, reducing carbon emissions and maintaining stable production (Yang et al., 2022; Zhou et al., 2023).

This study will review the current situation and challenges of rice cultivation in subtropical regions, analyze the development and advantages of mechanical direct seeding technology, and determine the optimal planting density and sowing date in the mechanical direct seeding system that can maximize yield, resource utilization efficiency and sustainability. By integrating recent research and field trials, this study aims to provide practical suggestions for farmers and policymakers to enhance the productivity and environmental sustainability of rice cultivation in subtropical regions. The research results are expected to promote the wider application of mechanical direct seeding technology, thereby supporting the future construction of resilient and profitable rice production systems.

2 Overview of Mechanized Direct-seeded Rice Cultivation Technology

2.1 Basic principles and processes of mechanized direct seeding

Mechanical direct seeding of rice is not a new concept, but in specific practice, it avoids the traditional seedling raising and transplanting steps and directly sows the rice seeds into the field with equipment. In terms of methods, they can roughly be divided into dry sowing and wet sowing. The tools used are adapted to local conditions, including precision row seeders and simplified drum-type equipment. Before planting, land preparation is essential. The depth and spacing of sowing should not be arbitrary either. All these need to be well coordinated with nutrient and weed management. If the sowing is accurate and the quantity is well controlled, the seedlings will emerge uniformly, there will be less seed waste, the input will be more efficient, and the returns will naturally not be bad (Sansen et al., 2019). However, not all regions remain unchanged. The differences between dry land and wetland require some adjustments in agricultural machinery and management in order for the technology to be truly implemented.

2.2 Comparison with traditional transplanting methods

When comparing mechanical direct seeding rice (DSR) with traditional transplanting rice (PTR), many people first think of how much labor and water can be saved. Indeed, this approach can save 15% to 50% of labor, eliminate the steps of seedling raising and transplanting, and reduce costs by 8% to 19%. In terms of water conservation, DSR also has advantages. It can significantly reduce irrigation water and has low energy consumption, which is conducive to emission reduction. However, one should not only focus on its advantages. It has higher management requirements and is more sensitive to weeds, water conditions and climate change. Studies have pointed out that in the case of inadequate management, the output of DSR may be 2% to 12% lower than that of PTR (Xu et al., 2019; Devi et al., 2024). Of course, this gap can be bridged through more precise operations. From an environmental perspective, although direct seeding reduces methane emissions and is beneficial to the soil, if management fails to keep up, nitrous oxide emissions may increase instead.

2.3 Application bottlenecks in subtropical regions

When it comes to promotion, especially in subtropical regions, things haven't gone so smoothly. A practical issue is that as the number of weeds increases, more pesticides are used, and the risk of herbicide resistance also rises. This requires a more complex integrated management plan to deal with. For instance, in low-lying areas or environments with frequent rainfall, it is not easy to keep the seedlings uniform and strong, and the problem of crop lodging occurs from time to time (Figure 1) (Jat et al., 2022). In addition, this method has high requirements for drainage. Once the fields are not unobstructed, the effect is often worse than that of traditional transplanting, and the yield cannot be significantly reduced. There is still a technical threshold for farmers. Many of them have never used live-streaming equipment and are not quite clear about how to fertilize and control weeds. Coupled with the lack of supporting training and services, it is naturally very difficult to promote. In terms of policy, mechanical subsidies and the lagging infrastructure construction are also major shortcomings. Therefore, although this technology has a promising future, for it to truly take root and blossom in subtropical regions, it still relies on more targeted research and policy support.

3 Effects of Sowing Date on Rice Growth and Development

3.1 Impact on germination and seedling stage

If sowing is done when the temperature is suitable and the light conditions are sufficient, the possibility of uniform and strong seedlings will be much greater. The period from mid to late May is often regarded as the "window period" for rice, during which the emergence rate is high, the seedlings are full of vitality and grow fast. Conversely, once the sowing is delayed, the seedling environment may not be so ideal. Either the temperature is too low or the light is insufficient. The germination rate will decrease and the entire growth period will be shortened (Shanta et al., 2020). In some years, if late sowing encounters extreme weather conditions, such as sudden heavy rain or continuous overcast days, the vitality and yield potential of the seedlings will be discounted. In contrast, an obvious advantage of early sowing is more warm accumulation, faster seedling development and a more solid foundation.

(a)

(b)

Figure 1 (a) Effect of adverse climatic conditions on the direct seeded rice crop. (b) Effect of adverse climatic conditions on the mechanically transplanted rice crop (Adopted from Jat et al., 2022)

3.2 Regulation of tillering, heading, and maturity by sowing date

The number of tillers, the timing of heading and the time of maturity are actually all related to the sowing time. Earlier sowing usually prolongs the vegetative growth period, significantly increases tillers in the field, leads to more leaf growth, and accumulates more dry matter. However, once the sowing is late, the time is compressed, there are fewer tillers and fewer panicles, and the yield also decreases accordingly. Some farmers missed the sowing period and had to postpone sowing by a few days. As a result, the heading period happened to coincide with the cold weather, and the seed setting rate of spikelets dropped sharply, and the filling also became a problem (Zheng et al., 2020). Overall, the period from mid-May to early June is usually quite stable. Whether it's the tillering stage, the heading stage or the maturation stage, the temperature is well-coordinated.

3.3 Relationship between sowing date and meteorological factors (temperature/rainfall)

Whether rice grows well or not, temperature and rainfall are two unavoidable factors, and these two are closely related to the sowing period. Sowing at the appropriate time not only ensures that the light can keep up, but also the temperature is just right. The photosynthetic efficiency is naturally high and the yield is more guaranteed. However, if the sowing is delayed until later, the heat accumulation will be insufficient, and the light is often inadequate. The seedlings will grow slowly during the seedling stage, and the yield in the later stage will be impossible to catch up. In some years, some sensitive varieties still encountered low temperatures at the heading stage after late sowing, and the seed setting rate decreased particularly significantly (Gao et al., 2024; Feng, 2025). There is also the issue of rain. If it rains too heavily during the sowing days, the seedlings may not grow at all. On the contrary, if it is too dry, no seedlings will emerge. Whether the sowing time is chosen well or not sometimes determines the success or failure of a season of rice.

4 Regulation of Yield and Population Structure by Planting Density

4.1 Effects on photosynthetic efficiency and leaf area index

Whether photosynthetic efficiency is affected or not, planting density is often an unavoidable variable. Leaf area index (LAI) is closely related to density. When density increases, LAI generally increases as well, and the ability to intercept sunlight also improves accordingly. However, it's not the case that the higher the density, the better. Too many leaves block each other, and the lower leaf surfaces cannot get sunlight, which instead slows down the net photosynthetic rate. On the contrary, a density that is too low is also not good. Although there is sufficient light, the overall photosynthetic output cannot be increased. The conclusions given by several studies are actually quite consistent: Moderate density is the safest and can enable the crop population to have a good performance in both biomass and dry matter accumulation (Zhao et al., 2024).

4.2 Mechanisms affecting panicle number, grain number, and seed-setting rate

When the density goes up, the number of ears will indeed increase, but this is only the aspect that seems to indicate a stable yield. In fact, in a high-density environment, water, fertilizer and light all need to be seized. After the competition intensifies, the number of grains per spike often drops, and the seed setting rate is also affected accordingly (Wang et al., 2022). Under low-density planting, although the total number of panicles is slightly smaller, the number of grains that each plant can support is actually greater, and each panicle can produce more seeds, which can somewhat make up for the loss in the number of panicles. However, one should not be overly optimistic. If the density is too low, there is also an upper limit to this "panicle grain supplementation" mechanism. Ultimately, it is still necessary to find that "critical point" - to keep both the number of panicles and the number of grains per panicle in an optimal state, so that the yield can be more stable.

4.3 Advantages and disadvantages under high and low density conditions

Under high density, the plants are densely distributed, and the field looks very "full". The growth is fast in the early stage, the biomass accumulation is large, and the yield is sometimes indeed high (Hou et al., 2019). However, the problems are not small either: excessive shading leads to poor grain filling, slow grain development, and it is also prone to lodging and pests and diseases. In the case of low density, although the number of panicles decreased somewhat, the grains were plump, the ventilation was good, the stem strength was improved, and the overall lodging rate was low (Bueno et al., 2023). However, it should be noted that the density cannot be reduced infinitely; otherwise, the total output may be held back due to insufficient number of ears. Ultimately, the setting of density depends on the variety, as well as the plot and climate. Neither too high nor too low is good. What matters most is suitability. Generally, slightly increasing the density can not only maintain the number of panicles but also help improve the grain filling rate. Most importantly, it is less likely to cause problems such as lodging or a drop in the photosynthetic efficiency of the population.

5 Interaction Effects Between Sowing Date and Planting Density

5.1 Mechanisms of joint regulation on growth period

The growth process of rice is ultimately driven by temperature and light conditions, but the adjustment of sowing time and planting density will play a role of "adding fuel to the fire" or "stepping on the brake" on this basis. Early sowing can prolong the vegetative growth period and is inherently beneficial for tillering. When a medium to high density is added, the population in the field will thrive, and the number of tillers and biomass will also increase accordingly. However, once sowing is delayed, the duration of sunlight shortens and the temperature fails to keep up, thus compressing the entire growth period significantly. At this point, even if you increase the density further, the tillering number is still prone to drop, especially in groups with intense competition for light and heat.

However, on the other hand, delayed sowing is not completely without remedial methods. For instance, by appropriately adjusting the planting density, the population structure and the accumulation of assimilation products can still be stabilized to a certain extent (Ji et al., 2024).

5.2 Interactive effects on population structure and yield components

Population structure and yield, which may sound like two separate systems, are actually tightly bound together under the combined effect of sowing time and density. Early sowing combined with high density is a typical "yield-increasing combination", which is particularly beneficial for the number of ears and grain filling. However, if the sowing is late and a high density is added, there will be many more troubles: the tillering utilization rate will be low, the number of spikelets will decline, and the seed setting rate will also be held back (Zheng et al., 2020). Of course, it is not to say that high density is completely useless under late sowing conditions. Some experiments have found that it can "replenish some yield", but when replenishment reaches a certain extent, the upper limit is reached. Continuing to increase density may have the opposite effect - lodging, diseases, and grain filling obstacles may all emerge. Overall, the best results often occur in stable combinations such as "early sowing + medium density", which not only ensures the number of ears but also guarantees that the grains can be irrigated.

5.3 Resource use efficiency under representative combinations

Not all sowing date density combinations can achieve both high yield and high efficiency. The truly outstanding resource utilization efficiency is often achieved when early sowing is combined with medium to high density - more light is used, water and nitrogen are not wasted, and the entire system operates more smoothly (Santiago-Arenas et al., 2022; Zhu, 2025). Some experiments simply compared the two sowing periods directly. The results showed that even if the nitrogen fertilizer was reduced a little, as long as the sowing was early and the density was properly controlled, the yield still increased and the grouting was more ideal (Zhou et al., 2023; Zhu et al., 2023). In contrast, the combination of late broadcasting and high density not only leads to an uneven distribution of resources but also amplifies the competitive pressure, thereby significantly lowering efficiency.

6 Case Study Analysis

6.1 Development of mechanized direct-seeded rice in South China

In South China, when it comes to how to grow rice more conveniently, many people first think of mechanical direct seeding. With the shortage of manpower and the annual increase in costs, coupled with everyone's focus on the "green and efficient" aspect, mechanical direct-seeded rice (DSR) has naturally been widely adopted. Especially for early-maturing indica rice, after the application of precise hole sowing and mechanical row sowing, both the yield and the ability to resist lodging have reached a new level. New techniques like furrow fertilization are also quite practical. The emergence rate, aboveground biomass and harvest index have all improved. Moreover, compared with full-layer fertilization or surface fertilization, the risk of lodging is much lower (Chen et al., 2021). However, it doesn't mean that direct seeding is fine. For instance, in this humid subtropical climate, when there is a lot of rain, direct seeding is very likely to cause soil erosion and phosphorus loss. Overall, the double-cropping rice system has made some optimizations in terms of sowing rate and nitrogen fertilizer management, which can indeed stabilize the yield and enhance the resistance to lodging.

6.2 Field experiment on direct-seeded rice in Shaoguan, Guangdong

A field test was also conducted in Shaoguan, and the location selected was quite representative - subtropical and hilly terrain. The study compared three mechanical direct seeding methods, namely dry seeding, water seeding and wet seeding, and used early-maturing indica rice. Over the past two years, it has been found that the yield of dry sowing has always been higher than that of water sowing, with an increase ranging from 6.6% to 26.3%. This advantage mainly stems from an increase in the number of panicles and better emergence. More importantly, plants sown under drought conditions grow strong, have more dry matter, grow faster, and have thick and solid stems. Even small details like short internodes at the base directly affect the lodging performance, and the lodging index naturally decreases. The research conclusion is clear: To carry out mechanical direct seeding in South China, if the sowing method is selected correctly and combined with suitable varieties, both yield and lodging resistance can be achieved simultaneously (Wang et al., 2021).

6.3 Optimal planting scheme selection and adaptability analysis

Which combination is the most suitable? At present, a combination of medium and high broadcast volume and moderate nitrogen reduction is a relatively reliable solution. This can not only increase the output but also reduce the lodging (Figure 2) (Wu et al., 2024). Going deeper, meticulous management techniques like Rapid Fertilization (FRF) also have the potential to further enhance yield stability. In terms of species, early-maturing indica rice is particularly suitable for direct seeding in double-cropping rice systems, which can be seen from the experimental performance. Both its yield and lodging resistance are not bad. But don't forget that the soil fertility and climate vary from place to place. To achieve success, it still depends on the management of specific plots as a guarantee. Especially in areas with abundant rainfall, if not properly managed, problems such as nutrient loss and even soil erosion are likely to occur. Overall, as long as it is equipped with appropriate agronomic measures, mechanical direct seeding rice can still gain a firm foothold in South China and become a good option for stable production, high efficiency and adaptation to climate change.

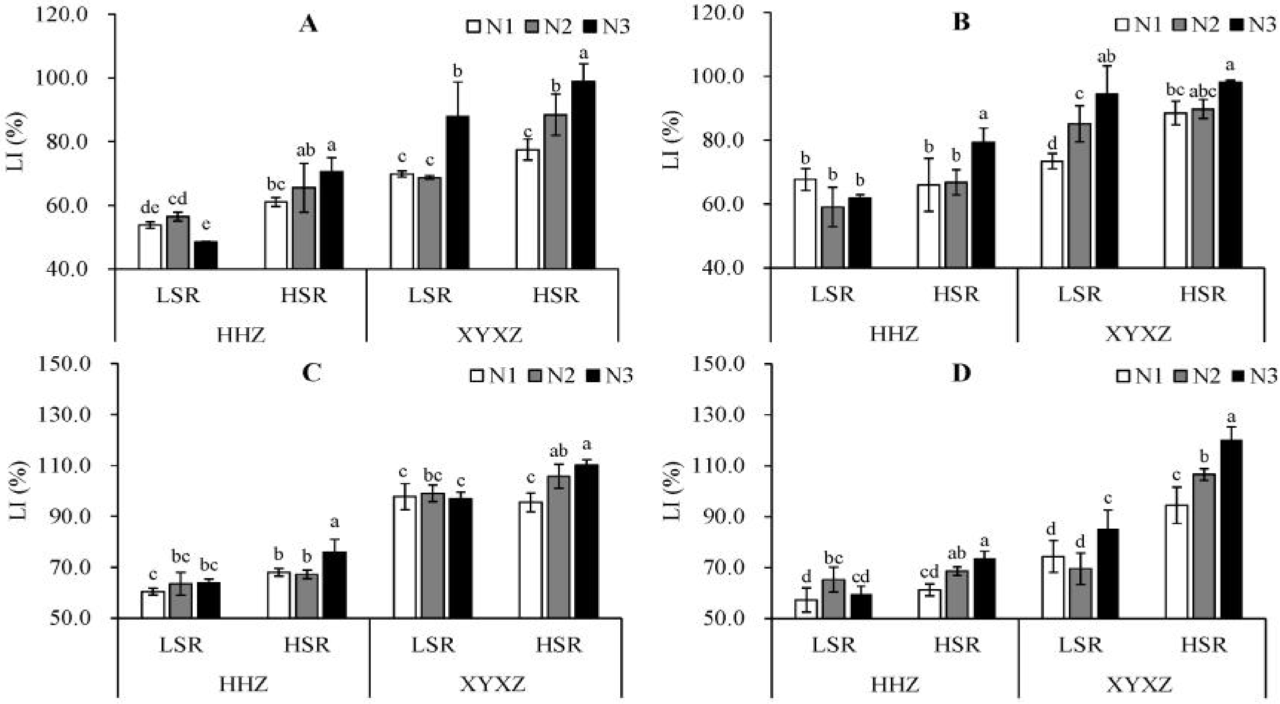

Figure 2 Lodging index (LI) under different seeding rates and nitrogen application rates in direct-seeded and double-season rice. (A-D) represented early season 2020, late season 2020, early season 2021, and late season 2021, respectively. LSR, low seeding rate (30 cm × 18 cm); HSR, high seeding rate (30 cm × 12 cm); N1, nitrogen fertilization at 100 kg/ha; N2, nitrogen fertilization at 150 kg/ha; N3, nitrogen fertilization at 200 kg/ha; HHZ, Huanghuazhan; XYXZ, Xiangyaxiangzhan. Different lowercase letters indicate statistical significance between treatments ($p < 0.05$) (Adopted from Wu et al., 2024)

7 Recommendations for Optimized Cultivation and Promotion

7.1 Recommended ranges for optimal sowing date and planting density

When is the best time to sow seeds? This issue cannot be addressed in a one-size-fits-all manner, but experience tells us that the 10 to 15 days before the start of the rainy season is a relatively safe time window, mainly to ensure sufficient soil moisture so that seeds can germinate smoothly and seedlings can grow solidly. In subtropical regions, it is usually from late May to early June. However, it is not accurate every year. The climate fluctuates greatly and specific arrangements should be made based on the local annual rainfall rhythm (Santiago - Arenas et al., 2022). In terms of density, the currently recommended mechanical row seeding rate is 30 to 70 kilograms per hectare. This range can balance uniform seedlings, reasonable density and maximum yield, and also control the cost of seed input. However, one should not merely focus on the broadcast volume; the depth of broadcast is equally crucial. Under dry sowing conditions, the seedlings are generally kept at a depth of 2 to 3 centimeters. For wet sowing, they should be slightly deeper, controlled between 3 and 5 centimeters, so that the seedlings can emerge more evenly and uniformly.

7.2 Supporting agronomic practices and machinery optimization

Don't expect to achieve success merely by "sowing seeds". The success or failure of direct rice cultivation hinges on meticulous attention to detail. The land should be leveled in the early stage. Weeding before sowing must be done properly. Herbicides like paraquat and glyphosate should be applied in advance. During the days after sowing, it is very important to keep the soil moist. Do not let the soil be too dry or too wet. For machinery, it is recommended to choose a seeder with a metering system, such as a tilting plate or cup meter, which can control the seeding amount and plant spacing more precisely, reducing seed waste and avoiding seed damage (Sansen et al., 2019). Weed control remains an old problem. It is best to combine pre-emergence and post-emergence herbicides with mechanical weeding to ensure stable yield. In terms of fertilization, it is a common practice to apply urea deeply and control the total amount of nitrogen fertilizer. This not only enhances the absorption efficiency but is also more environmentally friendly. The selection of varieties cannot be ignored. Direct-seeded rice is more suitable for those types with solid root systems, short growth periods and strong adaptability, so that both resistance and yield can be achieved.

7.3 Policy support and feasibility for large-scale promotion

To enable DSR to be implemented in more places, relying solely on technology is not enough; policy support is also crucial. For instance, subsidies for the purchase of agricultural machinery, farmer training, and the promotion of water-saving technologies are all practical measures that can encourage farmers to try DSR. In addition, some places have built confidence through demonstration projects. When farmers see the fields growing well with their own eyes, the acceptance is naturally high. However, some environmental issues also need to be taken seriously, such as soil erosion and nutrient loss. This requires policies to encourage the use of conservation tillage methods and support more targeted research. If DSR can be incorporated into national-level food security strategies or climate response plans, its promotion potential and influence will undoubtedly be greater (Dubey et al., 2024).

8 Conclusion and Prospects

The promotion of mechanized direct seeding rice (DSR) in subtropical regions is not a new topic, but it is not easy to achieve a balance among yield, resource utilization and stress resistance. Recent studies have shown that an appropriate sowing period combined with a reasonable planting density can indeed make DSR perform as well as traditional transplanting, and even outperform it in some traits, such as the number of tillers and the number of grains per panicle. However, such advantages cannot be guaranteed to be reproduced under all conditions. Compared with transplanting rice, the "savings" in seed and fertilizer usage achieved by DSR seem considerable. It has indeed led to an increase in nitrogen fertilizer utilization, a reduction in production costs, and a decrease in carbon footprint. However, what growers are most concerned about is still stable production. Once management fails to keep up, soil water retention is poor, or sudden meteorological anomalies occur, the yield of direct-seeded rice may not be so "reliable". In addition, the increased difficulty in controlling weeds and the easy loss of nutrients have also made many farmers have concerns about DSR.

So, for live-streamed rice to truly "stand firm", it still relies on a complete set of more meticulous agronomic solutions. Weed management, water and fertilizer regulation, and selection and breeding of suitable varieties - none of these can be missing. However, these technologies cannot rely solely on a few sets of data from experimental fields. Future research requires long-term and cross-regional tracking, especially in the context of climate change. The performance differences among different sowing Windows and density combinations are worth systematic exploration.

In addition, while solving problems through seeds and management measures is one aspect, the coordination of policies, promotion and training cannot be lacking either. Even if the varieties are of the best quality and the machines are the most advanced, without appropriate technical guidance, it is hard to guarantee that the field effects will not be compromised. The next direction of efforts may focus on several key words: new materials with stronger root systems, greater stress resistance, and better ability to compete with weeds for territory. More intelligent decision support tools; There are also more sustainable nutritional and weed control methods. Only through the concerted efforts of all parties can direct seeding rice truly take root firmly in subtropical regions, achieve stable and efficient production, and be sustainable.

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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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