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Abstract

A typical blade-type branch chipper was used to study the effects of rotor speed, feed mass and branch diameter class on chipping performance. Chipping efficiency and the qualified particle-size rate (percentage of output particles ≤30 mm) were adopted as evaluation indices. Single-factor tests and an L9(3^3) orthogonal experiment were carried out to analyze the influence of each factor on these performance indices. The results showed that branch diameter class had the most significant impact on performance: small-diameter branches significantly improved both chipping efficiency and the qualified particle-size rate. Rotor speed and feed mass exhibited positive effects within appropriate ranges, each with an optimal interval. The orthogonal test confirmed a significant synergistic effect among the three factors, and the optimal parameter combination was determined to be a rotor speed of 2500 r/min, a feed mass of 6.5 kg per batch, and small branch material. These results provide a theoretical reference for improving the performance of branch chippers.

Key words: branch chipper; chipping efficiency; qualified particle-size rate; orthogonal analysis

Introduction

Across many developing regions in Asia, Africa, and Latin America, agricultural production is still dominated by smallholder farming systems. Farmland is highly fragmented, the stock of agricultural machinery remains limited, and many field operations continue to rely heavily on manual labor (Özoğul, 2018; Emami *et al.*, 2018). In orchards and forestlands, pruning, renewal, and thinning generate substantial amounts of woody branch residues. However, the lack of suitable equipment and a reliable system for collection and utilization means that these residues are often piled along field margins and rural roads or burned on site. Such practices not only occupy arable land and reduce operational space, but also intensify non-point source pollution and greenhouse gas emissions, thereby posing risks to both the local environment and farmers' health (Georges *et al.*, 2011; Pari *et al.*, 2018). Developing affordable, on-site mechanized solutions for processing branch residues and other woody biomass wastes is therefore a practical priority for promoting green agricultural transformation and circular agriculture in many developing countries.

Chipping woody branches and using the chips on site for mulching and soil return, composting, or as a biomass fuel offers an effective route for valorizing woody residues (Poje *et al.*, 2015;

Manzone *et al.*, 2013; Prada *et al.*, 2015). In this context, branch chippers with a simple structure, small-to-medium power demand, and good mobility and serviceability are better suited to regions where electricity supply and road access are limited, as well as to small-scale farm operations. However, the equipment most commonly used in rural areas of developing countries is often general-purpose or locally replicated, and its design typically targets a single crop or relatively controlled, industrial conditions. As a result, these machines are seldom optimized for field realities such as large variation in branch diameter class and irregular feeding during operation (Houmy *et al.*, 2013; Aberilla *et al.*, 2019; Simonyan *et al.*, 2013). By contrast, imported machines in some cases face barriers including high purchase cost, oversized power requirements, and maintenance challenges, which limits their adoption among small and medium smallholders.

Previous studies indicate that the operating performance of chipping/shredding systems is governed by the coupled effects of multiple working-condition parameters. Among these, rotor speed, feed mass, and the diameter of the incoming branches are consistently identified as key determinants of both throughput efficiency and particle-size quality (Spinelli *et al.*, 2013; Manzone *et al.*, 2015; Spinelli *et al.*, 2021). For agricultural and forestry residues such as straw and pruned branches, researchers have examined shredder configurations, blade geometry, and powertrain matching, among other aspects. However, much of this work has emphasized structural design and theoretical analysis, while systematic experiments and performance evaluation under representative field conditions remain comparatively limited. This gap is particularly evident for parameter matching and optimization under the constraints of small-power equipment typically used by smallholders in developing countries (Osei *et al.*, 2024; Jibrin *et al.*, 2013; Mani *et al.*, 2004). In addition, current performance assessment approaches often rely on a single metric -such as theoretical capacity or installed power- which makes it difficult to capture the combined outcome of efficiency and product quality across different parameter settings. This limitation reduces the practical value of evaluation results for equipment selection and for optimizing operating conditions in the field.

From the practical needs of agricultural development in many developing countries, branch-chipping equipment should not only be simple in structure, easy to service, and affordable, but also able to deliver high chipping efficiency and consistent particle-size quality under limited power supply and relatively harsh operating conditions (Spinelli *et al.*, 2001; Assirelli *et al.*, 2013;

Spinelli *et al.*, 2011). Accordingly, it is necessary to use a representative small-to-medium branch chipper as the test platform and to select key operating and material parameters- such as rotor speed, feed mass, and branch diameter class- for a systematic multi-factor experimental study. Such an approach can quantitatively clarify the individual effects and coupled interactions of these factors on chipping performance and further enable the development of a concise and practical method for performance evaluation and parameter optimization. The resulting evidence can provide technical support for scaling up the adoption of appropriate branch-chipping equipment in rural areas of developing countries.

In this study, a representative blade-type branch chipper was selected as the test machine. Chipping efficiency and the qualified particle-size rate were used as the primary performance metrics. A set of single-factor experiments and an L9 (3^3) orthogonal design were conducted with three factors: rotor speed, feed mass, and branch diameter class. By comparatively analyzing the experimental results, the main effects of each factor and their relative importance on chipping performance were determined, and an operating parameter combination that balances efficiency with particle-size quality was recommended. These findings provide practical parameter guidance for valorizing orchard and forest pruning residues in regions such as Asia, Africa, and Latin America, and they also offer a basis for structural improvement and control strategy development for small-to-medium power branch chippers in developing countries.

Overall configuration and operating principle of the branch chipper

Machine configuration

As shown in Figure 1, the branch chipper mainly consists of a feeding unit, a chipping unit, an electric motor, a screening system, a base/frame, a discharge outlet, and a control system. The feeding unit typically adopts a twin-roller compression design to deliver branches into the chipping chamber at a stable rate. The chipping unit is the core module of the machine and comprises rotating blades, a stationary counter-blade, and a blade disc mounted on a high-speed main shaft; it cuts the incoming branches into small chips. The screening system is installed at the downstream end of the chamber and uses sieves with different mesh openings to regulate the particle-size distribution of the chipped material. The base and frame carry the loads of the main components and provide structural support and protection. Coordinated control of the main-shaft motor and the feed motor is achieved through the controller.

Operating principle

The operating sequence of the branch chipper is as follows. Branches are manually fed into the inlet and are conveyed into the chipping chamber by the feed rollers. The main-shaft motor runs at high speed and drives the blade disc; under centrifugal force, the rotating blades extend outward and work together with the stationary counter-blade to shear and split the branches. As the material undergoes high-speed cutting and repeated impacts, it is progressively broken down into granular chips. Meanwhile, the rotating disc and chamber geometry generate a circulating airflow that transports the chipped material toward the screening section.

When the chips reach the screen, particles smaller than the screen openings are guided by the airflow to pass through and exit the machine. Oversized pieces are retained by the screen and rebound back into the chipping zone, where they continue to be cut until the target particle size is achieved. Some machines include a recirculation path to return non-qualified material for repeated processing, which improves size uniformity and overall productivity. During operation, the electronic control system monitors parameters such as rotational speed, current, and load in real time, enabling overload protection and interlock control to maintain stable and safe performance.

Experimental design

To systematically evaluate the operating performance of the branch chipper under different parameter settings, this study focuses on how key factors—namely rotor speed, feed mass, and branch diameter class—affect chipping efficiency and the qualified particle-size rate. The aim is to establish a sound performance assessment framework that can support subsequent optimization of operating conditions and the development of control strategies (Table 1).

Experimental platform and instrumentation

Experiments were conducted on a self-built branch-chipping test platform consisting of a feeding module, a chipping module, a screening unit, and an electrical control cabinet. The drive motor had a rated power of 5.5 kW and a rated speed of 2800 r/min. The blade disc diameter was 450 mm and was equipped with six rotating blades and two stationary blades. The control system enabled variable-frequency speed control of the main shaft and adjustment of the feed speed. The screening assembly used a standard round-hole screen that could be quickly replaced to test different opening sizes. The measurement instruments included an electronic balance (0.1 g resolution), a three-phase power analyzer, an infrared thermometer, a vernier caliper, a sound level meter, and a high-resolution camera, which were used to collect operating data in real time and to capture images for particle-size evaluation.

The test materials were fresh pruned poplar branches. Before each experiment, the branches were sorted according to diameter class. The branch length used in the tests was controlled at approximately 250–300 mm, and branches with obvious defects such as decay or severe cracking were excluded to reduce material variability.

Experimental variables and factor levels

Single-factor tests were first conducted to examine the response trends of chipping efficiency and the qualified particle-size rate to each key factor. During these tests, the other variables were held at their mid-level settings (rotor speed: 2200 r/min; feed mass: 6.0 kg per batch; material: medium-diameter branches). Rotor speed, feed mass, and branch diameter class were then varied individually to quantify their respective influences.

Afterwards, a three-factor, three-level L9 (3^3) orthogonal design was employed to investigate combined effects. The factor levels were set as follows: rotor speed of 1900, 2200, and 2500 r/min; feed mass of 5.5, 6.0, and 6.5 kg per batch; and three branch diameter classes, including small branches (<20 mm), medium branches (20–35 mm), and large branches (>35 mm). The range analysis results of the orthogonal tests are summarized in Table 2.

Performance metrics and calculations

Two key indicators were used to evaluate the chipping performance in this study:

(1) Chipping efficiency (kg/h): the total mass of chipped material discharged per unit time.

(2) Qualified particle-size rate (%): the mass percentage of chips with particle size ≤30 mm, determined by sieving, relative to the total sample mass.

For the particle-size evaluation, a representative sample of chipped material was collected after each test and sieved using a standard 30 mm round-hole screen. The qualified particle-size rate was calculated as the mass percentage of particles passing through the screen. Each operating condition was repeated 3 times, and the average value was used for analysis.

Results and Discussion

Effect of rotor speed on chipper performance

Figure 2 illustrates how chipping efficiency and the qualified particle-size rate change with rotor speed. As the rotor speed increased from 1600 r/min to 2500 r/min, chipping efficiency rose from 485 kg/h to 618 kg/h, representing a 27.4% increase, while the qualified particle-size rate improved from 78.1% to 91.2%, an increase of 16.8%. This improvement can be attributed to the higher cutting frequency at elevated disc speed, which enhances the loading and cutting action on branches and thus strengthens size reduction and particle-size control. However, when the rotor speed exceeded 2500 r/min, both indices declined. This may be because excessively high blade speed shortens the effective blade–material interaction time and increases branch rebound or slip in the chamber. At the same time, the stronger internal airflow and more intense impact motion can disturb stable material transport and discharge, which ultimately reduces both throughput and particle-size uniformity.

Effect of feed mass on chipper performance

Figure 3 shows the trends in chipping efficiency and the qualified particle-size rate under different feed masses. As the feed mass increased from 5.0 kg to 6.5 kg, chipping efficiency rose from 467 kg/h to 618 kg/h, corresponding to an increase of 32.3%. Over the same range, the qualified particle-size rate improved from 77.5% to 91.2%, increasing by 17.7%. These results suggest that a moderate increase in feed mass helps utilize the processing capacity of the chipping unit, raises the amount of material processed per unit time, and stabilizes the cutting load on the blades, thereby improving particle-size control. When the feed mass further increased to 7.0 kg, chipping efficiency continued to rise, but the qualified particle-size rate decreased. This suggests that excessive feeding increased material accumulation and instantaneous cutting load in the chamber, thereby reducing cutting uniformity and allowing some insufficiently chipped fragments to be discharged before adequate size reduction.

Effect of branch diameter class on chipper performance

Figure 4 presents the variations in chipping efficiency and the qualified particle-size rate for different branch diameter classes. As the material shifted from small branches (<20 mm) to large branches (>35 mm), chipping efficiency decreased from 618 kg/h to 498 kg/h, corresponding to a reduction of 19.4%. Over the same change in diameter class, the qualified particle-size rate declined from 91.2% to 76.7%, decreasing by 15.9%. This trend is mainly due to the larger diameter and denser fibrous structure of thick branches, which increases cutting load and size-reduction resistance. As a result, the processing capacity per unit time decreases, and the material is less fully reduced, generating more oversized chips that lower the qualified particle-size rate. In contrast, small branches are lighter and thinner, present lower cutting resistance, and are more readily chipped and screened, leading to the best overall performance.

Multi-factor orthogonal experimental analysis

To quantify the effects of rotor speed, feed mass, and branch diameter class on chipping performance and to determine an optimized parameter combination, a three-factor, three-level L9 (3^3) orthogonal design was conducted. Chipping efficiency (kg/h) and the qualified particle-size rate (%) were used as the evaluation indices. The orthogonal test matrix was established and range analysis was performed, with the results summarized in Table 2.

To further visualize the main-effect trends of each factor, main-effects plots were generated to show how the factor levels influence chipping efficiency and the qualified particle-size rate, as presented in Figure 6.

Both the range analysis and the main-effects plots indicate that branch diameter class has the most pronounced influence on chipping efficiency and the qualified particle-size rate. Its range values reach 92.44 for chipping efficiency and 13.33 for the qualified particle-size rate, which are substantially higher than those of the other factors. Consistent with the single-factor results, small branches perform best overall because their smaller dimensions impose a lower cutting load, making it easier to achieve both higher throughput and a higher qualified particle-size rate compared with medium and large branches. Rotor speed and feed mass also affect the two indicators within the tested ranges. When rotor speed increases from 1900 r/min to 2500 r/min, the mean chipping efficiency rises by 34.33 kg/h and the qualified particle-size rate increases by

2.67%. As feed mass increases from 5.5 kg per batch to 6.5 kg per batch, the mean chipping efficiency improves by 40.33 kg/h, and the qualified particle-size rate also increases, indicating that moderate increases in rotor speed and feed mass can enhance overall performance.

Accordingly, the factor importance for chipping efficiency follows the order branch diameter class > feed mass > rotor speed, whereas for the qualified particle-size rate it follows branch diameter class > rotor speed > feed mass. To determine the optimal operating combination, both chipping efficiency and the qualified particle-size rate were considered simultaneously. Because small branches produced the best results for both indices, this level was selected first. Within this condition, a rotor speed of 2500 r/min and a feed mass of 6.5 kg per batch were chosen because they yielded the highest or near-highest average responses and provided the most balanced improvement in throughput and particle-size quality. Therefore, the recommended parameter combination is 2500 r/min, 6.5 kg per batch, and small-branch material.

These findings are in general agreement with previous studies reporting that material characteristics and operating conditions jointly determine chipper productivity and chip-size distribution. In particular, larger branch diameter class increases cutting resistance and reduces size-reduction uniformity, while appropriate rotor speed and feed level help maintain stable cutting action and discharge. Therefore, the present results not only confirm the importance of parameter matching for small-to-medium branch chippers but also provide practical guidance for field operation under variable branch conditions.

Conclusions

This study investigated a representative blade-type branch chipper through systematic experiments focusing on three key operating parameters: rotor speed, feed mass, and branch diameter class. The main conclusions are as follows:

(1) Rotor speed had a clear effect on performance. When rotor speed increased from 1600 r/min to 2500 r/min, chipping efficiency rose from 485 kg/h to 618 kg/h, and the qualified particle-size rate increased from 78.1% to 91.2%. When rotor speed exceeded 2500 r/min, both indicators declined, indicating the presence of an optimal speed range.

(2) A moderate increase in feed mass improved both capacity and chipping quality. At a feed mass of 6.5 kg per batch, chipping efficiency and the qualified particle-size rate reached relatively

high levels. However, excessive feeding caused material congestion and less uniform particle size, which negatively affected chipping performance.

(3) Branch diameter class strongly influenced machine load and product quality. Small branches (<20 mm) required lower cutting resistance and achieved the best performance, with chipping efficiency of 618 kg/h and a qualified particle-size rate of 91.2%. In contrast, large branches (>35 mm) were more likely to produce oversized chips, leading to inferior size quality.

(4) Orthogonal analysis confirmed branch diameter class as the dominant factor. Small branches consistently produced the highest chipping efficiency and qualified particle-size rate. Rotor speed and feed mass also showed positive contributions, and the optimal combination was identified as 2500 r/min rotor speed, 6.5 kg per batch feed mass, and small-branch material. This setting delivered the best overall balance between efficiency and particle-size quality, supporting the feasibility of improving performance through coordinated parameter selection.

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Table 1. Operating-condition parameters.

Parameter	Value	Unit
Rotor speed	1600-2800	r/min
Feed mass	5.0-7.0	kg/batch
Branch diameter class	Small branches / medium branches / large branches	-

Table 2. Range analysis results of the orthogonal experiment.

Factor	Level	Mean chipping efficiency (kg/h)	Range, R	Mean qualified particle-size rate (%)	Range, R
Rotor speed	1900	547.56	34.33	85.33	2.67
	2200	566.89		87.33	
	2500	581.89		88.00	
Feed mass	5.5	543.89	40.33	85.44	2.33
	6.0	568.22		87.44	
	6.5	584.22		87.78	
Branch diameter class	Small branches	597.00	92.44	92.11	13.33
	Medium branches	561.56		86.44	
	Large branches	504.56		78.78	

Figure 1. Overall view of the branch chipper.

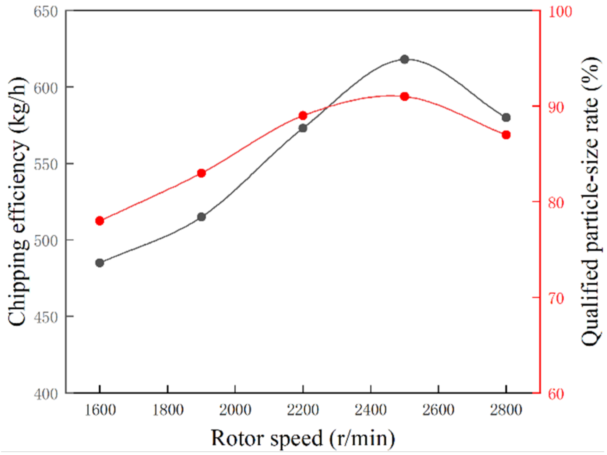

Figure 2. Variation in branch chipper performance at different rotor speeds.

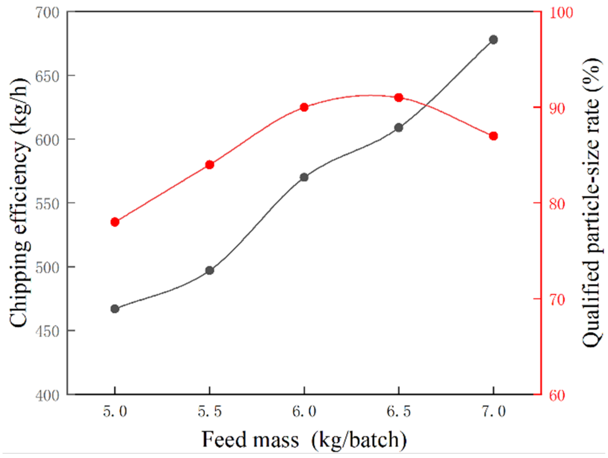

Figure 3. Variation in branch chipper performance at different feed masses.

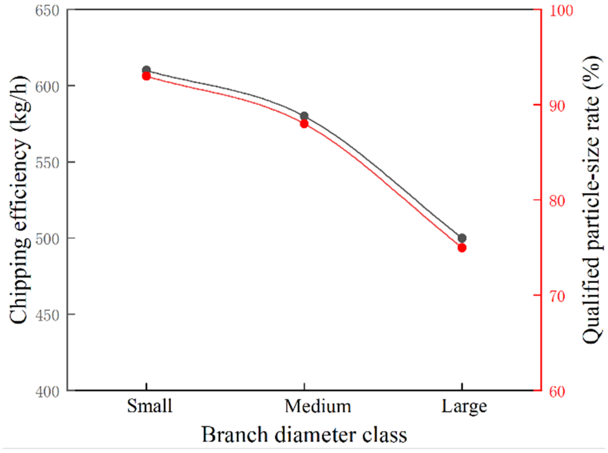

Figure 4. Variation in branch chipper performance for different branch diameter classes.

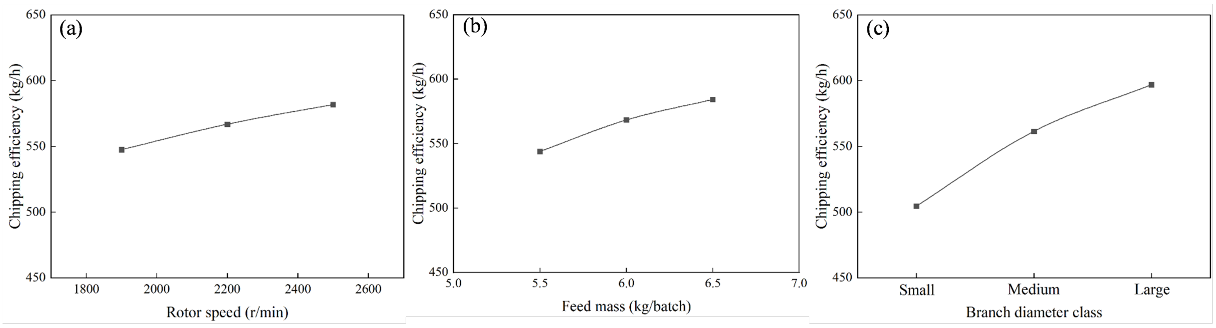

Figure 5. Main-effects response curves of factor levels for chipping efficiency.

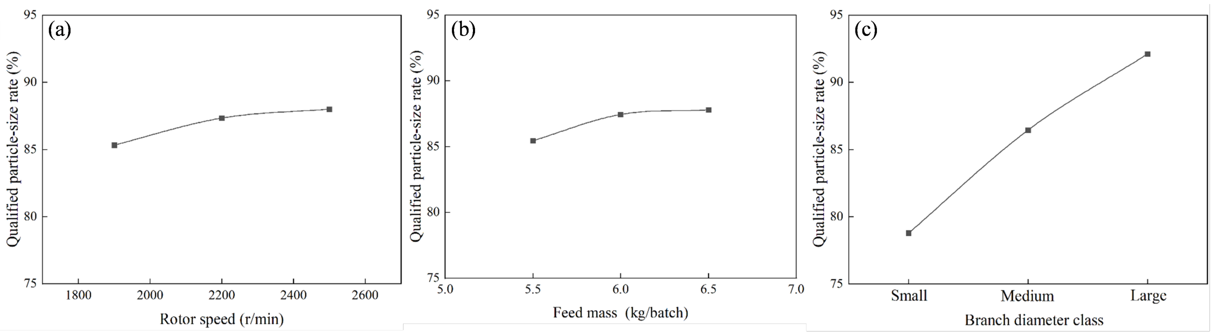

Figure 6. Main-effects response curves of factor levels for the qualified particle-size rate.