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ORIGINAL ARTICLE

Dimensional analysis of the adequacy of agricultural machinery for biomass handling in agroforestry systems[1]

Análise dimensional da adequação de máquinas agrícolas para manejo de biomassa em sistemas agroflorestais

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HIGHLIGHTS:

The coastal brushcutter excels in small plots, promoting robust grass regrowth and optimal biomass yield with low fuel costs.
Mini grain reaper machine provides the quickest raking times and the lowest operational costs.
Tractor-mounted rotary brushcutter operates faster and reduces operator strain, but it has higher costs and less accuracy.

ABSTRACT: Agroforestry Systems (AFS) integrate trees, agronomic crops and forage species, focusing on agricultural sustainability and productivity. However, the lack of specific mechanization for AFS limits their efficiency. This research aimed to assess the adequacy of existing agricultural machinery for biomass handling in AFS and thus contribute to solving the issue of lack of specific mechanization in AFS for family farming, in order to foster the expansion of AFS lands. This study assessed three types of machinery for handling Mombaça grass (*Megathyrsus maximus* Jacq): coastal brushcutter (CBC), tractor-mounted rotary brushcutter (RBC), and mini grain reaper machine (GRM) throughout three cutting cycles. The dimensional analysis and Likert scale methods were employed for assessment of cutting height, handling time, labor cost, fuel consumption, regrowth speed, dry matter weight, and raking time of cut grass. Obtained through dimensional analysis, Pi-terms Π_1 and Π_3 represent, respectively, the treatment's quality of cut and financial cost. The binomial $\Pi_1 \times \Pi_3$ represents the cost-benefit ratio. CBC was suitable for small areas, to guarantee better grass regrowth rate, and higher biomass production, while providing the best cost-benefit ratio for fuel. GRM was the most adequate for obtaining the lowest operational costs, the lowest time required for raking up cut grass, higher biomass production, providing the best financial estimate for fuel. RBC was indicated for faster work, handling at higher scales, and considerably reduced physical strain.

Key words: *Megathyrsus maximus* Jacq, agroecosystems, mechanization, family farming, forest farming

RESUMO: Sistemas Agroflorestais (SAFs) integram árvores, culturas de interesse agronômico e forrageiras, visando sustentabilidade agrícola e produtividade. Contudo, a falta de mecanização específica para SAFs limita sua eficiência. Esta pesquisa objetivou avaliar a adequação das máquinas agrícolas no manejo da biomassa em SAFs e contribuir para a solução do problema da falta de mecanização específica para SAFs cultivados pela agricultura familiar. O estudo avaliou três tipos de máquinas para o manejo do capim Mombaça (*Megathyrsus maximus* Jacq): roçadora costal (CBC), roçadora rotativa montada ao trator (RBC) e mini colhedora de grãos (GRM) ao longo de três ciclos de corte. Os métodos da análise dimensional e escala Likert foram empregados para a avaliação da altura de corte, tempo de manejo, custo de mão de obra, consumo de combustível, velocidade de rebrota, peso de matéria seca e tempo de amontoa. Os Pi-termos Π_1 e Π_3 representam, respectivamente, a qualidade do corte e o custo financeiro. O binômio $\Pi_1 \times \Pi_3$ representa a relação custo-benefício. A CBC foi adequada para pequenas áreas, garantindo melhor vigor de rebrote, maior produção de biomassa e expressou a melhor relação custo-benefício. A GRM foi indicada para obter os menores custos operacionais, o tempo mais rápido necessário para amontoar o capim cortado, a maior produção de biomassa e a melhor previsão financeira de custo com combustível. A RBC foi adequada para realizar o trabalho mais rapidamente, para manejo em escalas maiores e para reduzir consideravelmente o esforço físico.

Palavras-chave: *Megathyrsus maximus* Jacq, agroecossistemas, mecanização, agricultura familiar, agricultura florestal

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INTRODUCTION

Agroforestry Systems (AFS) are sustainable agricultural practices that boost productivity while minimizing environmental impact. By integrating trees with crops and forage species, AFS maximizes biomass production, addressing challenges such as food security, farmer livelihoods, and environmental resilience (Kuyah et al., 2019). AFS improve soil health through mulching, enhance fertility, reduce temperature variation, provide organic matter to support soil life, control weeds without chemicals and increase water stress tolerance (Silva et al., 2022; Primavesi & Primavesi, 2023). Abundant soil life facilitates continuous organic matter decomposition, enriching the soil and benefiting plant growth.

AFS are complex due to the cultivation of multiple species, requiring constant pruning, harvesting, and organic matter management. For family farmers, who rely on family labor, including women and children, this work is exhausting and inefficient, limiting the area they can manage (Sanjuán & Migliorini, 2023). The lack of machinery and supportive policies further hinders their ability to compete with conventional farmers, as AFS are often organic systems. When diversifying crops, family farmers also face challenges such as limited inputs, knowledge, technology, funds and market access (Kundu et al., 2020; Guo & Zhao, 2021).

This work addresses the lack of mechanization in AFS by tracing methods to adapt existing machines for AFS tasks. The obtained knowledge and recommendations aim to improve efficiency for family farmers, providing valuable insights for farmers, technicians, and policymakers. This aims to enhance the efficiency of the workload required by family farming, in which AFS serve as a source of income in situations with limited labor.

This research focuses on managing grass biomass grown between rows in a specific AFS model, which includes economically valuable trees and bushes, with interrows containing Mombaça grass, which is extensively used in AFS due to its notably high yield and rapid production rate compared to other grass cultivars. The harvested grass is used as soil cover to enhance soil properties (Kaur et al., 2022). Its biomass, with high levels of carbon, contributes to the slow decomposition of organic matter, which in turn remains longer and protects the soil (Das et al., 2016). Using common machines for interrow management can reduce manual labor and boost productivity and market competitiveness.

This study tested three agricultural machines: coastal brushcutter, tractor-mounted rotary brushcutter, and mini grain reaper machine. The first was also used by Almeida et al. (2019) to manage weeds in intercropping systems and by Mesquita et al. (2024) to cut different forages, including Mombaça grass. The second is commonly used for cutting plants and distributing them on the soil (Santos et al., 2021), clearing scrub in the understory of tree plantations (Ferreiro-Domínguez et al., 2022) and mowing vegetation (Brito et al., 2021). The last machine has been explored as an alternative to manual machines for cereal crop harvesting, as it can improve time management and reduce labor and field losses (Gupta et al., 2020).

The growing demand for machinery tailored to biomass handling in AFS underscores the need for optimized equipment. This study uses dimensional analysis to compare machine performance based on mass, length, and time (MLT), to assess the adequacy of current machinery. By examining plant and equipment properties, areas for improvement can be traced, thereby supporting future designs. Albiero et al. (2011) demonstrated the method's effectiveness. Dimensional analysis also promotes resource optimization, reduces repairs, minimizes the need for spare parts (Yalyna, 2021), and determines and quantifies key parameters affecting machine performance for biomass handling. This method creates dimensionless charts and Pi-terms that represent parameter relationships and performance impact.

This research aimed to assess the adequacy of existing agricultural machinery for biomass handling in AFS and thus contribute to solving the issue of lack of specific mechanization in AFS for family farming, in order to foster the expansion of AFS lands.

MATERIAL AND METHODS

This study examined the mechanization of the handling of Mombaça grass (*Megathyrsus maximus* Jacq) cultivated within a specific type of AFS. In this model, economically valuable tree species are planted in rows, while the interrow spaces, filled with grass, serve the role of producing the highest amount of biomass possible. There is periodic cutting of grass biomass, which is then deposited as soil cover on the rows where the economically valuable tree species are planted.

This study assessed three types of machines for grass cutting: two brushcutters using blade impact - one featuring a front cutting mechanism, referred to as the coastal brushcutter (CBC), and the other with a rear cutting mechanism, known as the tractor-mounted rotary brushcutter (RBC). These machines were chosen for being common and affordable for family agriculture in the regional market, based on the hypothesis that agroforestry handling can be optimized with available machines.

Additionally, a mini grain reaper machine (GRM), traditionally used for harvesting rice and wheat, was included for its superior front cutting system, enabling comparison of grass response to different cutting methods. Although imported and less affordable, the GRM's less aggressive cutting system preserves healthier grass clumps, which is hypothesized to enhance biomass production over successive cuts. Given the distinct cutting systems of each machine, plant regrowth and subsequent biomass productivity may vary across cutting cycles.

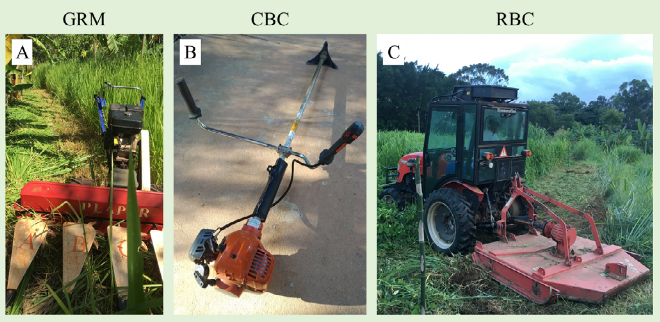
The dimensional analysis method was employed to research this hypothesis. This method, was prefigured by Murphy (1950) and Taylor (1974), described by Langhaar (1951) and Szücs (1980), and applied by Albiero et al. (2011) in agricultural machinery. To facilitate the understanding of the results, it was used the Likert Scale (Likert, 1932). This is applied worldwide as a summative scale and is the most used model to measure attitudes, preferences and perspectives.

The study was performed in the South-eastern region of Brazil, specifically at Brazilian Agricultural Research Corporation (EMBRAPA), in Jaguariúna, São Paulo, Brazil (22° 43' 28.41" S and 47° 0' 56.08" W), with minimum altitude of 570 m and maximum altitude of 620 m (Santos & Calderano Filho, 2000). The experimental site spanned 5 hectares. The prevailing soil in the area is categorized as Dystrophic Red-Yellow Oxisol (Santos et al., 2018), featuring a sandy-clay-loam texture and a moderate A-horizon (Neves et al., 2017). Additionally, the region exhibits characteristics of a subdeciduous tropical forest phase, with annual average temperature of around 22 °C. The average annual precipitation exceeds 1,300 mm, with rainfall concentrated in the summer. The average annual air humidity is 76.3% (INMET, 2025).

The experiment replicated the interrow areas of AFSs by cultivating grass plots with the same width as typically found in AFS interrows: 6 m. It was conducted in monoculture, as rows of economically valuable tree species were not planted. The study employed a randomized block design (Costa, 2003) to collect data on the variables under analysis. This design comprised six blocks, with each block containing three plots that, in turn, represented a particular treatment (machine). The grass was submitted to three cuttings over the course of the year-long study.

Each block measured 49 × 6 m, totaling 294 m^2, with plots measuring 13 × 6 m (78 m^2). Maneuvering areas between plots were 5 × 6 m (30 m^2). The total grass planting area was 1404 m^2 and the total block area was 1764 m^2. After each grass cutting cycle, 3 sample units measuring 50 × 50 cm (0.25 m^2) were randomly marked in each plot. Data on post-cut grass development, including regrowth speed (RS), cutting height (CH), and count of basal tillers and regrowths, were collected from these units. Dry mass (DM) samples were collected from 1 m^2 units, sharing the same vertex as the previously marked sample units.

For the experiment setup, soil preparation involved plow harrowing, leveling harrowing, and subsoiling. It was applied 62 kg of natural phosphate fertilizer at a rate of 437.5 kg ha^{-1}, according to the calculation based on the soil analysis. Blocks and plots were marked to designate sowing areas. Grass was sown manually at a density of 3 kg of pure viable seeds per hectare, following the method outlined by Kichel & Kichel (2001). After seed emergence and grass growth, a standardized cut was performed using a tractor-mounted rotary brushcutter. Initially, all grass in plots and blocks was cut with the same machine, with subsequent cuts conducted according to treatments.



GRM - Mini grain reaper machine; CBC - Coastal brushcutter; RBC - Tractor-mounted rotary brushcutter

Figure 1. Tested machines: GRM (A), CBC (B), and RBC (C)

Three machines were chosen (Figure 1): two brushcutters (CBC and RBC) and one reaper machine (GRM).

CBC is a portable machine weighing up to 14 kg with rotating blades powered by a small motor connected to a cutting disc. The operator wears a supporting belt. The specific model used is the Husqvarna 143R-II, powered by gasoline with a 41.5 cm^3 cylinder volume engine, delivering 1.5 kW (2.01 hp) at a maximum speed of 7,500 rpm, with a fuel tank capacity of 0.95 L. The tests used a three-tooth cutting blade.

RBC is an implement connected to a tractor and powered by it. It is used for cutting grass and controlling weeds. The experiment used a Jumil JM-RUTD-A 1.4, year 2010, series 185.045-1, with a cutting width of 1.3 m and height adjustable from 2 to 10 cm. It has two rotating blades (from 800 to 1,100 rpm), weighs 342 kg, and measures 1.5 m wide, 1.95 m long, and 1.13 m high. The tractor used to drive it is a Tramontini T5045-4, 4 × 4 model from the Brasil Cafeeiro series, with a width of 1,170 m, hydraulic controls, PTO from 540 to 1,000 rpm and a 50 CV power engine.

GRM is a reaper machine, model 4G-120A, self-propelled, with minimum cutting height of 5 cm, 1.2 m working width, 2.05 m long, 0.57 m high, works at a speed of 2.6 to 6.2 km h^{-1}, weighs up to 120 kg, gear transmission, engine power of 6.6 kW (9 CV), consumes 8.15 to 12.11 liters ha^{-1} of gasoline. The cutting system consists of the dividing assembly, which acts to separate and direct the material to the cutting blades. After cutting, the conveyor chain and star wheels work to push the biomass to the right and deposit it on the ground. Imported from China, it was designed for harvesting grains such as rice and wheat and is controlled by an operator walking behind it.

The experiment encompassed three grass cutting cycles: April to November 2021 (fall, winter, and spring); November 2021 to January 2022 (spring and summer); and January to April 2022 (summer and fall). A cutting cycle denotes the duration between successive grass cuts, indicating the time required for the plant to regenerate for harvesting. The length of these cycles varies, with fall and winter cycles being longer than spring and summer cycles, dictated by the pace of grass growth across different seasons.

Seven variables were measured: regrowth speed (RS - cm per day) (Oliveira et al., 2000; Bernache et al., 2020), cutting height (CH - cm) (Dixit, 2022; Silva et al., 2020), handling time (HT - s ha^{-1}), fuel consumption value (FC - L R\$ ha^{-1}) (ASABE, 2009; ANP, 2022), labor cost (LC - s R\$ ha^{-1}) (IEA, 2022), dry matter weight (DM - kg ha^{-1}) (Dubis et al., 2019; Silva et al., 2020) and raking time for cut grass (RT - s ha^{-1}). The data collection methods used were described by Morais et al. (2023). To conduct dimensional analysis effectively, all values were expressed in consistent units of measurement (Albiero et al., 2011). Specifically, data were aligned with the GCS system, representing MLT (mass, length and time) as gram (g), centimeter (cm) and second (s), respectively. An extensive assessment of mechanical, agronomic, economic, and labor factors was carried out. The analysis employed Pi-terms, constant dimensionless factors to represent interconnected behaviors among independent parameters and allow proportional quantification of their variations. This approach resulted in multiple straight lines with varying angular coefficients in the dimensionless charts, thereby considerably facilitating the interpretation of results.

As described by Albiero et al. (2014), there are seven steps for calculating the Dimensional Analysis: i) conversion of parameters into generic variables (named as "K1," "K2," etc.) and only with basic dimensions of MLT; ii) preparation of the dimensional matrix that is composed of the basic dimensions exponents; iii) preparation of the sub-space matrix through the selection of the three most important variables in the dimensional matrix: DM, RS and RT (DM was chosen as the most important variable, as the goal is to maximize biomass production, RS was selected for its direct relation to cutting quality, and RT for addressing the extra labor required to manage the biomass produced between rows); iv) definition and resolution of the linear equations system, which are three equations equal to zero, obtained by multiplying the exponents of each dimensional matrix variable, where they are different from zero; v) definition of Pi-terms through the solution matrix, which consists of the values of "K" obtained in the system of linear equations; vi) creation of the correlation matrix using Pearson's product correlation coefficient (Snedecor & Cochran, 1989) to find which Pi-terms have better correlated behaviors; vii) preparation and analysis of dimensionless charts, made from binomials that have correlation coefficients greater than 0.85 on a scale from -1 to 1.

Π_1 and Π_3, presented respectively by Eqs. 1 and 2, were calculated according to the seven measured variables: regrowth speed (RS), cutting height (CH), handling time (HT), fuel consumption value (FC), labor cost (LC), dry matter weight (DM) and raking time for cut grass (RT):

$$\Pi_1 = \mathrm{CH} \times \mathrm{RS} \times \mathrm{RT} \tag{1}$$

where:

Π_1 - cutting quality;
CH - cutting height;
RS - regrowth speed; and,
RT - raking time for cut grass.

The relationship between the variables in Eq. 1 (CH, RS and RT) demonstrates that Π_1 represents cutting quality. It does so by taking into account CH and RS, respectively, the factors responsible for keeping the apical meristem intact or not and the plant regrowth after cutting. Cutting quality is also related, in this Pi-term, to the resulting biomass physical state after cutting, which is represented by the time required to drag and rake the biomass (RT).

$$\Pi_3 = \mathrm{FC} \times \mathrm{RS} \times \mathrm{RT} \tag{2}$$

where:

Π_3 - financial cost;
FC - fuel consumption value;
RS - regrowth speed; and,
RT - raking time for cut grass.

The relationship between the variables in Eq. 2 (FC, RS and RT) indicates that Π_3 provides a means of relating the machines' financial cost to their cutting quality. The cost refers to the FC measured in each treatment. Cutting quality, just as the previous Pi-term, takes into account RS and RT.

Dimensionless charts were built based on the binomial $\Pi_1 \times \Pi_3$, which were the Pi-terms that demonstrated the strongest behavioral correlations, presenting correlation coefficient values above 0.85.

The calculation of the minimum number of samples that needed to be collected in each plot of the experiment, so there is normality in the experiment, was obtained according to the method described by (Montgomery & Runger, 2002), in which the mean standard error is calculated and plotted in the operating characteristics curves chart.

The Likert scale (Likert, 1932) was built based on the results of each treatment regarding the evaluated variables and the dimensionless analysis. This method provided a better analysis of the experimental results for a better understanding of the machines' adequacy for AFS handling. Through this approach, Table 2 was prepared to summarize and compare the treatments effectively. Data from each variable were used independently to build the table, as were data produced by dimensionless graphs (obtained through dimensional analysis). Data from individual variables were used to support the discussion and provide a more detailed description of the performance of treatments, while data from the dimensional analysis consider this issue as a whole.

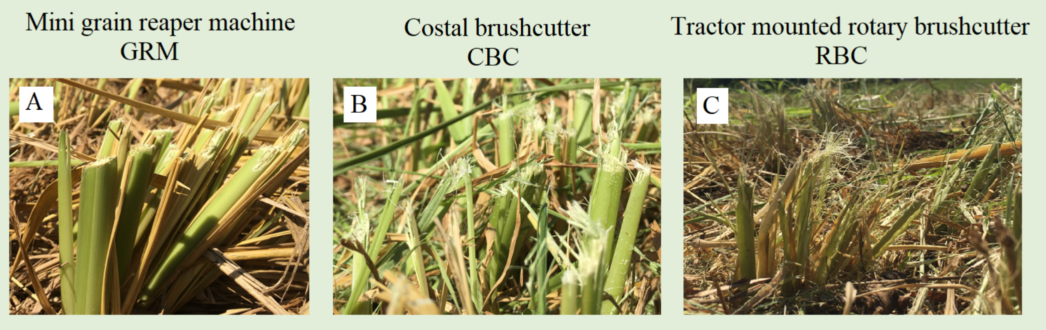
To this end, each treatment parameter was classified from 1 to 3. As suggested by Likert (1932), the classification was based on the average values of the parameters, with 1 assigned to those considered least satisfactory, 2 to the average results, and 3 to the most satisfactory. The same was done for the binomial $\Pi_1 \times \Pi_3$. The table was then designed to allow comparison of the parameters measured over time. For the binomial $\Pi_1 \times \Pi_3$, its values were assigned based on graphs comparing cutting cycles between treatments (Figures 6, 7, and 8).

RESULTS AND DISCUSSION

Figure 2 shows the results for cutting at the grass clumps for the three tested machines: mini grain reaper machine (GRM), coastal brushcutter (CBC) and tractor-mounted rotary brushcutter (RBC). It shows the difference in the quality of the cutting systems.

GRM showed the highest cutting quality among the tested machines, causing minimal damage to the clumps and preserving the apical buds. Sahoo & Raheman (2020) also observed high cutting efficiency of reaper machines. Their precise cutting, characteristic of their reaping mechanism, exposed only the tissues at the cut area without creating cracks in the remaining clumps, minimizing impact and promoting plant recovery.

CBC showed intermediate cutting quality. While it preserved the apical buds, the cut resulted in greater exposure of internal tissues, hindering healing and increasing vulnerability to water loss and pathogen contamination. Compared to the GRM, its less precise impact-based cutting mechanism caused



GRM - Mini grain reaper machine; CBC - Coastal brushcutter; RBC - Tractor-mounted rotary brushcutter

Figure 2. Results for cutting at the grass clumps for GRM (A), CBC (B) and RBC (C)

more damage to the grass; compared to the RBC's two-blade system, its three-tooth cutting blade provided better results, consistently with Parcianello et al. (2022), according to whom this latter blade improves operational capacity and efficiency.

RBC showed the most aggressive performance, causing significant damage to the clumps, including destruction of the apical buds. The impact-based cutting mechanism, using thicker blades, caused extensive cracks in the clump remnants, exposing large internal areas and significantly increasing the risks of contamination and water stress. This is consistent with Bukhtoyarov et al. (2022), who demonstrated that, for RBCs, cutting elements other than rotary blades, such as knife chains, provide higher cutting quality.

Table 1 presents the coefficient of variation (CV) for Pi-terms Π_1 and Π_3 across three cutting cycles for each equipment. Π_1 and Π_3 represent, respectively, cutting quality and financial cost.

Cycle 1, during Autumn and Winter, exhibited low biomass and slower grass growth, enabling easier and more consistent machine operation. CBC exhibited the lowest CVs for Π1 (25.38%) and Π3 (23.13%), reflecting high consistency in cutting quality and costs under these conditions. GRM showed moderate CV for Π1 (32.01%) but high CV for Π3 (50.98%), indicating significant variability in financial efficiency, possibly due to initial calibration. This is consistent with the findings of Veselovska et al. (2021) that segment-finger mowers, like those used in GRM, are simple, reliable, and require less energy for grass mowing. RBC showed moderate variability (Π1: 47.68%; Π3: 46.76%), consistently with the use of robust machinery with fixed costs under low-density conditions, since they are generally more efficient in high-yield forage conditions.

During Cycle 2 (Spring), characterized by increased rainfall and grass growth, CBC maintained moderate CVs (Π1: 35.19%; Π3: 30.76%), highlighting its efficiency in smaller areas, even under higher biomass conditions. GRM showed a higher CV for Π1 (45.32%) but a lower CV for Π3 (29.10%), suggesting it managed to stabilize its operating costs but faced greater difficulty maintaining cutting uniformity as biomass increased. Gana et al. (2023) highlight that using larger harvesters can improve efficiency in high-yield tasks. Accordingly, RBC showed reduced variability (Π1: 39.13%; Π3: 32.59%), likely due to better adaptation to moderate biomass increases, suggesting that its higher cutting capacity contributed to its more stable performance.

Table 1. Coefficient of variation - CV (%)

Cycle	RBC [1]		GRM [2]		CBC [3]	
	Π_1	Π_3	Π_1	Π_3	Π_1	Π_3
1	47.68	46.76	32.01	50.98	25.38	23.13
2	39.13	32.59	45.32	29.10	35.19	30.76
3	52.05	31.28	79.75	68.31	117.00	90.66

[1] Tractor-mounted rotary brushcutter; [2] Mini grain reaper machine; [3] Coastal brushcutter

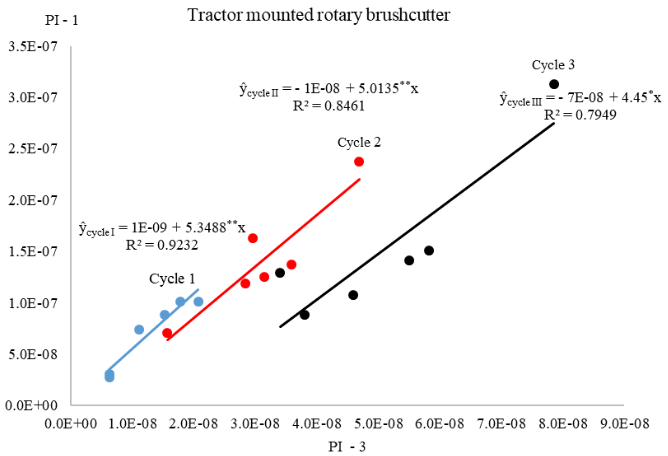
Cycle 3, during Summer, exhibited maximum biomass production due to warmer and rainy weathers. CBC showed extremely high CVs (Π1: 117.00%; Π3: 90.66%), highlighting operational challenges in dense biomass and high humidity, which can overwhelm lightweight machines. GRM exhibited high variability (Π1: 79.75%; Π3: 68.31%), reflecting its mechanical susceptibility to failures in environments with abundant vegetation, with Hassan et al. (2015) similarly reporting obstruction in GRM for bean harvest; however, it performed better than CBC, demonstrating some adaptability to dense areas. RBC demonstrated stability in Π3 (31.28%) despite an increase in Π1 (52.05%), underscoring its robustness and ability to maintain cost predictability under critical conditions, even as cutting quality declined; however, it still performed better than the other machines.

The dimensionless charts $\Pi_1 \times \Pi_3$ represent the treatment's cost-benefit ratio, that is, the correlation between cutting quality (Π_1) and financial cost (Π_3). Since Π_3 refers to the FC, the cost in this instance is directly associated with the FC. Mathematically, each point on the chart is a ratio between the cutting quality and the cost of fuel consumed.

Firstly, for the purpose of analyzing each treatment's performance, dimensionless charts were prepared for each treatment over the three cutting cycles: RBC (Figure 3), GRM (Figure 4) and CBC (Figure 5).

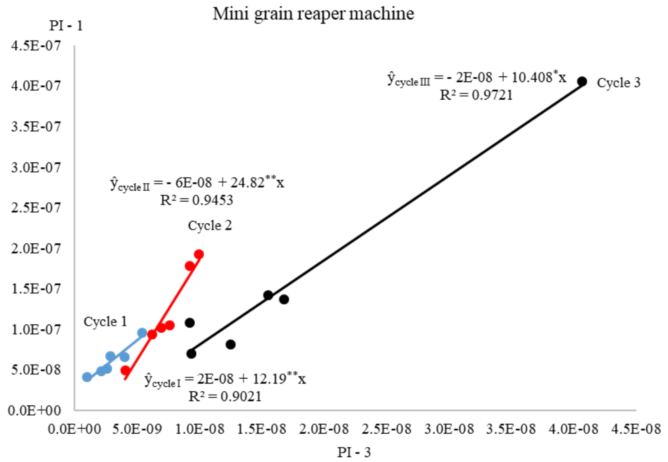
This section analyses each treatment's performance over the three cutting cycles, through the dimensionless charts: RBC (Figure 3), GRM (Figure 4) and CBC (Figure 5). This is consistent with Viana et al. (2024), who showed that water, energy and production are indicators for measuring sustainability in agricultural systems, as this research assesses energy consumption and grass production.

In general, the ideal post-cutting behavior of grass - specifically in the hotter and more humid periods of the year - is faster regrowth and higher biomass production. Barioni & Ferreira (2007) observed seasonal behavior for the accumulation of grass forage, with 77% of production recorded in the rainy season and 23% in the dry season. Similarly, Corsi et al. (2001) and Souza et al. (2005) found dry matter production from 75 to 85% in the hot and rainy season,



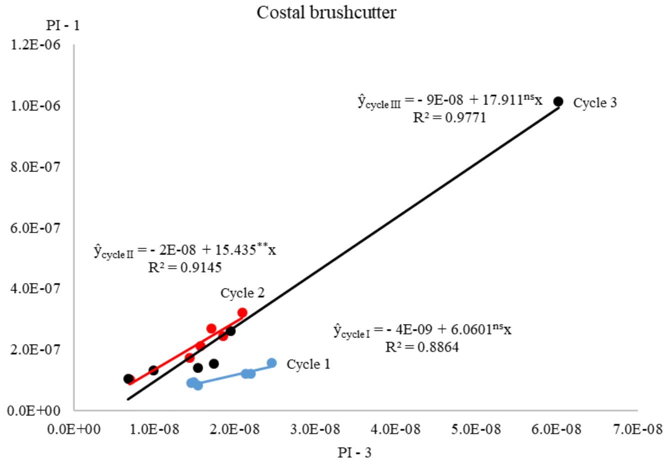
** - Significant by F test at $p \leq 0.01$; * - Significant by F test at $p \leq 0.05$

Figure 3. Tractor-mounted rotary brushcutter (RBC) dimensionless chart $\Pi_1 \times \Pi_3$ for the three cycles (C1, C2 and C3)



** - Significant by F test at $p \leq 0.01$; * - Significant by F test at $p \leq 0.05$

Figure 4. Mini grain reaper machine (GRM) dimensionless chart $\Pi_1 \times \Pi_3$ for the three cycles



** - Significant by F test at $p \leq 0.01$; ns - Not significant

Figure 5. Coastal brushcutter (CBC) dimensionless chart $\Pi_1 \times \Pi_3$ for the three cycles

between October and March. The cutting cycles occurred in different seasons, with cycle 1 (C1) in fall and winter, cycle 2 (C2) in spring - a hotter and more humid season than the previous one -, and cycle 3 (C3) in summer - which is the hottest and most humid season.

Therefore, a progressive increase in plant response values is expected after cutting, represented by the "Y" axis of the chart (Pi-1), starting from C1, passing through C2 and up to C3. Due to the higher volume of biomass to be cut in the last cycles, it is expected that the FC, represented by the "X" axis of the chart (Pi-3), will also gradually increase. Bukhtoyarov et al. (2022) also confirmed that brushcutters demand more energy when cutting higher amounts of biomass.

Charts must be interpreted in order to compare the behavior of the straight lines in the different cutting cycles, as, according to Albiero et al. (2014), dimensionless charts generate different straight lines with different angular coefficients to facilitate the interpretation of results. As for the cost-benefit ratio, a pattern of progressive increase in the position of the straight line is expected, such that its position in C1 would be more to the left and below the line in C2 and that the line in C3 would be more to the right and above the other lines. Another phenomenon can also be observed in this chart: the FC financial forecast. It can be observed according to the variation in the position of the straight lines on the "X" axis. The same pattern of interpretation of dimensionless charts was adopted by Albiero et al. (2011) when comparing straight lines obtained from data collected before and after experiments with agricultural machinery.

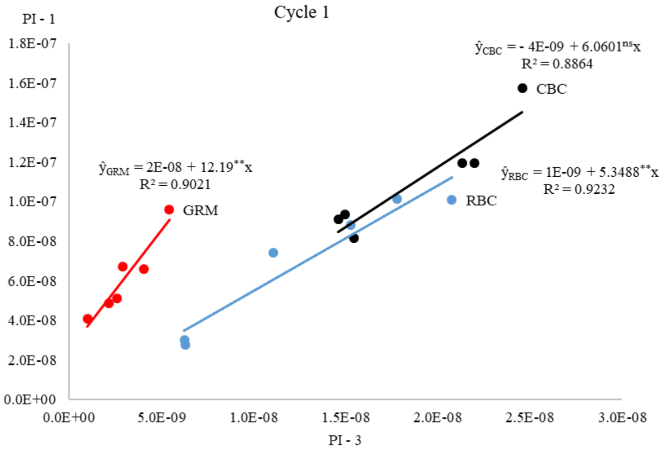
Thus, it is noted that the cost-benefit ratio pattern of dispersion of points and position of straight lines, as previously described, was observed for the RBC and for the GRM. Regarding the CBC, it is noted that the pattern positioning of the lines for cost-benefit ratio is not followed, which is possibly due to this machine being more susceptible to operator variations, since it is not a self-propelled machine. CBC operators experience high physical strain and musculoskeletal disorders (Carvalho et al., 2021), which can affect precision. Additionally, working postures influence muscle activity (Yang et al., 2022) and the use of proper attachments helps reduce vibration effects (Cella et al., 2022), both of which impact operator performance.

Here, it is demonstrated that the GRM treatment has a higher financial forecast. It was observed by the minimum variation in the position of the straight lines on the "X" axis (0 to 4E-08) compared to the other treatments (0 to 8E-08 for RBC and 0 to 6E-08 for CBC).

Secondly, in order to compare treatment performance, dimensionless charts were built for each cutting cycle, presenting all treatments: Cycle 1 (Figure 6), Cycle 2 (Figure 7) and Cycle 3 (Figure 8).

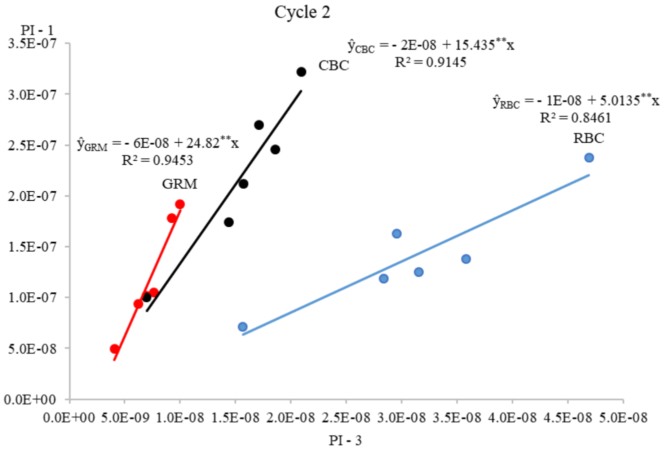
This section compares the treatment performances in each cutting cycle through the dimensionless charts: Cycle 1 (Figure 6), Cycle 2 (Figure 7) and Cycle 3 (Figure 8). The best cutting type is that for which cut quality and plant response values (Pi-1, "Y" axis in the chart) are higher, while the FC values (Pi-3, axis "X") are lower. The chart must be interpreted in order to compare the behavior of the straight lines, and the best results are observed in the charts according to the location of the lines. The straight lines positioned higher and more to the left demonstrate the most satisfactory results.

In addition, the interpretation of the charts must consider the straight lines' behavior over the cutting cycles. Given that single-cut harvest regimes in grass stands can increase forage



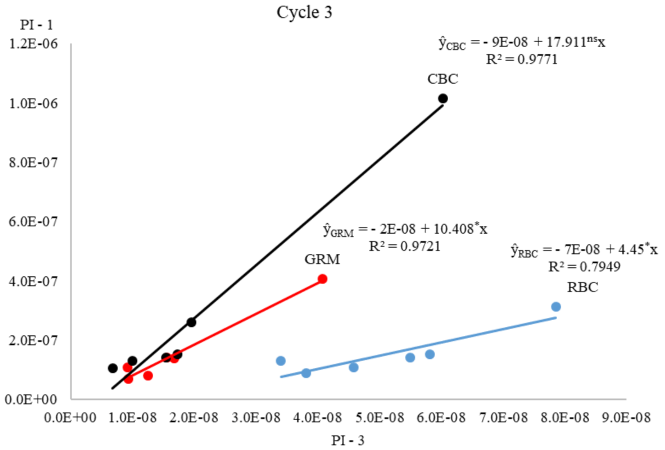
** - Significant by F test at $p \leq 0.01$; ns - Not significant. RBC - Tractor-mounted rotary brushcutter; GRM - Mini grain reaper machine; CBC - Coastal brushcutter.

Figure 6. Cycle 1 dimensionless chart $\Pi_1 \times \Pi_3$ for the three treatments: RBC, GRM and CBC



** - Significant by F test at $p \leq 0.01$ level. RBC - Tractor-mounted rotary brushcutter; GRM - Mini grain reaper machine; CBC - Coastal brushcutter.

Figure 7. Cycle 2 dimensionless chart $\Pi_1 \times \Pi_3$ for the three treatments: RBC, GRM and CBC



* - Significant by F test at $p \leq 0.05$; ns - Not significant. RBC - Tractor-mounted rotary brushcutter; GRM - Mini grain reaper machine; CBC - Coastal brushcutter

Figure 8. Cycle 3 dimensionless chart $\Pi_1 \times \Pi_3$ for the three treatments: RBC, GRM and CBC

biomass by up to 50% (Temu et al., 2022), it is expected that the grass responds differently when submitted to successive cuts according to each cutting system. This phenomenon is observed on the charts by the lines' detachment from one treatment to the other over time. In other words, throughout the successive cuts, the straight line that moves its location towards the left side and above, as it detaches from other lines, expresses the best cost-benefit ratio.

Thus, it can be observed in the chart that the CBC treatment obtained the most satisfactory results regarding the benefit of obtaining better plant response values. The CBC straight lines are located above the others in the three cutting cycles, which demonstrates the superiority of the treatment's cutting quality. Moreover, it is noted that, in cycle 1, the CBC straight line is located close to the RBC line and far from the GRM line; in cycle 2, the CBC line moves away from the RBC line and approaches the GRM line; and, in cycle 3, the CBC line is characterized as the line positioned furthest to the left, which is the most satisfactory location as it demonstrates the lowest values for FC.

This proves that CBC is the treatment that exhibited the best cost-benefit ratio over the successive cuttings. Firstly, because it obtained the best plant response in all cycles, a phenomenon favored by the best cutting quality. In addition, the change in the location of its straight line over the cutting cycles, culminating in this line being located more to the left in cycle 3, proves that this treatment results in the lowest FC cost over time. He et al. (2019) note that non-working distances also impact overall fuel consumption, reinforcing the advantage of lighter and manually-transported equipment.

In cycle 1, the CBC straight line is located further to the right than the others, which represents the highest FC. This can be due to this machine being the most susceptible to operator variations, since it is not a self-propelled machine.

In cycles 2 and 3, the RBC straight line was located more to the right compared to the others, thus characterizing this treatment as that with the highest FC. This was due to factors such as: being the largest and heaviest machine, with higher fuel consumption per working time; and the fuel used - diesel -, which, according to ANP (2022), was more expensive than gasoline in the experimental period.

GRM obtained the most satisfactory results for FC in cycles 1 and 2, according to the leftmost positioning of its straight line. However, in cycle 3, when the grass was cut in the summer, a period in which - according to Barioni & Ferreira (2007), Corsi et al. (2001), and Souza et al. (2005) - the amount of biomass to be cut was higher than the other cycles, the machine had excessive obstruction in its cutting system. It was necessary to stop the machine several times to clear it during the work. This led to considerably increased handling time for this treatment in the last cycle and its straight line approximating the RBC line. As a result, the GRM presented higher FC values than the CBC, but still lower than the RBC.

Hassan et al. (2015) also observed the same obstruction effect in a GRM for bean harvest in Egypt, which resulted in production losses of more than 50%. The authors attributed that to the excessive load of plants on the cutter bar.

The GRM obtained the most satisfactory results for the FC forecast, since this treatment obtained the smallest variation in the charts' "X" axis, which concerns the FC in all cutting cycles. As for cutting quality and plant response for the GRM and RBC treatments, there was no considerable difference between them, since their lines vary similarly on the charts'

Table 2. Likert scale of the variables according to the treatments across the three cycles

Treatment	Cutting cycle	CH	RS	DM	HT	RT	FC	LC	C x B	FFF
GRM	1st	2	3	3	2	3	3	3	2	3
	2nd	2	2	3	2	3	3	3		
	3rd	3	2	3	2	3	2	2		
CBC	1st	1	2	3	1	1	1	1	3	2
	2nd	1	3	3	1	2	2	1		
	3rd	1	3	3	1	2	3	1		
RBC	1st	3	1	1	3	2	2	2	1	1
	2nd	3	1	1	3	1	1	2		
	3rd	2	1	1	3	1	1	3		

Mini grain reaper machine; Coastal brushcutter; Tractor-mounted rotary brushcutter; Cutting height; Regrowth speed; Dry matter; Handling time; Raking time; Fuel consumption; Labor cost; Cost-benefit ratio; Fuel financial forecast; 1 - Less satisfactory; 2 - Average; 3 - More satisfactory

"Y" axis in all cutting cycles. The Likert Scale method was applied to facilitate the understanding of the results (Table 2).

This section discusses the machines' adequacy for handling the Mombaça grass biomass in AFS through the Likert scale (Table 2). Regarding the variables observed in the plant, the RBC presented higher CH homogeneity due to being a self-propelled machine, in which the CH is previously set and tends to be maintained by the machine; it also presented CH values low enough to damage the plant apical meristem, a fact that resulted in the grass regrowth almost exclusively by the emission of new basal tillers.

The CBC cutting system was responsible for the best grass RS results, possibly because of its higher CH, as suggested by Black & Alexander (1967), which resulted in less apical meristem destroyed and more leaf area for photosynthesis; both CBC and GRM cutting systems resulted in similar and higher DM productions than RBC, possibly because this latter treatment showed the lowest CH, consistently with Woodis & Jackson (2008), who found the lower the CH, the lower the DM production following the cut. However, grasses not always respond equally to CH. Bebawi et al. (1992) and Osman & Abu-Diek (1982) found higher DM production at lowers CH, while Watt & Haggar (1980) observed no effect in DM yields of grasses submitted to various CH. This proves that cutting quality is also important for increased harvest yields.

DM production is one of the most relevant parameters to indicate the machine with the best cutting system that, due to the successive grass cuttings, makes the plant respond with higher biomass production.

Regarding the working time parameters, RBC showed the best HT results, as it was the fastest machine. GRM presented the best RT results due to the integrity of the grass leaves and the way they were deposited on the ground - in bundles -, which resulted in less time to rake the grass. Regarding the financial cost parameters, GRM was responsible for the best results, observed by the lowest FC and LC values.

When observing the binomial $\Pi_1 \times \Pi_3$ dimensionless charts, CBC was considered the best treatment for the cost-benefit ratio; GRM presented the best FC forecast. RBC presented the worst values for the cost-benefit ratio and financial forecast. Albiero et al. (2014) and Albiero et al. (2011) also used dimensionless charts to provide information for analysis of the dynamics of physical phenomenon properties regarding agricultural mechanization. Table 3 compiles all findings on the most suitable situations for using the machines, aiming at better contextualization.

Table 3. Machines' suitability

Machine	Most suitable for:
GRM	Dry matter production
	Raking time
	Fuel consumption
	Labor cost
	Fuel cost forecast
CBC	Dry matter production
	Regrowth speed
	Cost-benefit ratio
RBC	Handling time

Mini grain reaper machine; Coastal brushcutter; Tractor-mounted rotary brushcutter

No single machine is ideal for all family farming needs, the choice depends on area size, budget, labor, and potential for hiring staff. Here, it is demonstrated that CBC is the most adequate machine to guarantee the best plant response over the successive cuts, which will result in better regrowth rate and higher biomass production with the lowest financial cost for fuel over time. CBC is especially adequate for smaller areas because it works slowly and reduces physical strain. This is consistent with Vorozhtsov et al. (2022), who emphasize the need for small-scale machinery in agriculture due to their adaptability and ease of maintenance, enabling small enterprises to access sufficient agricultural equipment.

It is also shown that GRM is the most adequate machine for lower raking time for cut grass or when the availability of labor is low; also to ensure higher biomass production; for lower total operating costs (fuel and labor); and for better FC forecast. GRM is especially indicated for farmers who are able to make adaptations, given the excessive obstruction presented in its cutting system during the experiment. GRM presented superior cutting quality, but its functionality made several analyzed parameters unsatisfactory.

Here, it is concluded that RBC is the most adequate machine for faster work and, therefore, for handling at larger scales. This treatment enables the lowest physical strain when compared to the others. Chouriya et al. (2024) also demonstrated that specific machinery reduces labor demand. RBC is also indicated for farmers who already have a tractor available for work. However, according to Palma et al. (2013), mechanized systems with large machines lead to higher soil compaction.

Conclusions

1. Based on dimensionless chart $\Pi_1 \times \Pi_3$ the coastal brushcutter is recommended due to the cost-benefit ratio; and the mini grain reaper machine due to the fuel cost forecast.

2. The Likert scale showed the best results provided by the treatments: Coastal brushcutter: regrowth speed and dry matter weight; Mini grain reaper machine: raking time for cut grass, fuel cost, labor cost, and dry matter weight; and Tractor-mounted rotary brushcutter: handling time.

3. Coastal brushcutter is suitable for small, rugged, and steep areas; mini grain reaper machine for increased dry matter production at reduced costs and lower raking time; tractor-mounted rotary brushcutter for large-scale handling.

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