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ORIGINAL ARTICLE

Experimental model for optimizing mechanized mountain coffee harvesting[1]

Modelo experimental para otimizar a colheita mecanizada do café de montanha

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HIGHLIGHTS:

Terrain slope does not impact the operational capacity of the prototype.
Harvesting losses are also unaffected by the terrain slope.
The prototype demonstrates a tenfold improvement in operational capacity.

ABSTRACT: Coffee holds significant economic and social importance for Brazil, being one of the main commodities in global agribusiness. Coffee growers, particularly those cultivating arabica coffee, face challenges due to labor shortages and high associated costs during manual harvesting. This study aimed to evaluate the operational performance and efficiency of a self-propelled coffee harvester prototype in terraced mountain areas. To assess harvesting losses, efficiency, and operational capacity, the experimental model traversed the designated area entirely. Fruit stripping was performed over the collection system at five different terrain incline angles (8°, 17°, 25°, 30°, and 38°). Harvesting loss was determined by the ratio of the mass of fruits retained by the collection system to the total mass of harvested fruits. For comparison, the efficiency and operational capacity of two workers performing manual fruit harvesting were also measured. Terrain slope did not significantly impact harvesting losses or operational capacity. The highest operational capacity was 0.11 ha h^{-1}, achieved at a 17° slope. The average operational efficiency was 66.2%.

Key words: *Coffea arabica*, machine design project, coffee harvesting, agricultural mechanization

RESUMO: O Brasil atribui significativa importância econômica e social ao café, o qual é uma das principais commodities do agronegócio global. Os cafeicultores, especialmente aqueles que plantam café arábica, enfrentam desafios devido à falta de mão de obra e aos altos custos associados à colheita manual. Este estudo teve como objetivo avaliar o desempenho operacional e a eficiência de um protótipo de colhedora autopropelida de café de montanha com terraços. Com o propósito de avaliar as perdas durante o processo de colheita, bem como a eficiência e a capacidade operacional, o modelo experimental percorreu integralmente a área designada. Durante esse percurso, foi efetuado a derriça dos frutos sobre o sistema de recolhimento, considerando cinco diferentes ângulos de inclinação do terreno (8°, 17°, 25°, 30°, 38°). A perda foi determinada pela relação entre a massa de frutos retidas pelo sistema de recolhimento e a massa total de frutos colhidos. A fim de realizar uma comparação do método mecanizado em relação ao método tradicional, também se determinou a eficiência e a capacidade operacional de dois trabalhadores que realizam a colheita manual dos frutos. A declividade do terreno não impactou de forma significativa as perdas na colheita e a capacidade operacional. O valor mais alto da capacidade operacional foi de 0,11 ha h^{-1}, alcançado em uma declividade de 17°. A eficiência operacional média foi de 66,2%.

Palavras-chave: *Coffea arabica*, projeto de máquinas, colheita de café, mecanização agrícola

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INTRODUCTION

Coffee harvesting can be conducted manually, semi-mechanized, or fully mechanized (Tikuneh et al., 2023). In the manual method, all stages, except transportation, are performed solely by workers without machine assistance. This approach poses significant challenges, including labor shortages and high operational costs. The lack of available labor is due to a limited labor supply in rural areas and the lower wages typically offered compared to urban areas (Souza et al., 2020). Labor scarcity leads to increased costs, which negatively impact production during the harvest period.

In mountainous regions, coffee harvesting is done using both manual and semi-mechanized methods, with portable coffee strippers playing a crucial role. In this system, at least two individuals usually work together: one skilled operator handles the coffee stripper, while the other is responsible for passing, lifting, and agitating the freshly harvested coffee cherries (Cunha et al., 2016a).

Agricultural terraces, common in mountainous areas, play a fundamental role in long-term sustainable agricultural production (Arnáez et al., 2015). This practice has attracted researchers' interest due to its focus on sustainability and the implementation of highly efficient structured management (Tarolli et al., 2014). These terraces, which can be up to 1.6 meters wide, allow for the passage of harvesting machines and compact tractors. A study by Alves et al. (2017) found that although terrace farming involves a high initial investment, it is economically viable based on economic indicators. Additionally, terraces facilitate manual labor by providing a flat surface for workers.

Previous studies have shown the potential of mechanization to address the challenges of coffee farming in mountainous areas. Oliveira & Teixeira (2013) developed and evaluated a self-propelled coffee harvester for mountainous regions, concluding that the harvester was stable on terrain with a 50% slope, superior to other harvesters on the market.

This study aimed to evaluate the operational performance and efficiency of a self-propelled coffee harvester prototype in terraced mountain areas.

MATERIALS AND METHODS

The prototype was tested in a commercial arabica coffee plantation (*Coffea arabica* L.) in Coimbra, Minas Gerais State, Brazil (20° 50' 58" S; 42° 47' 28" W), at average altitude of 850 meters, covering 59.66 hectares. The climate is classified as Aw according to the Köppen-Geiger classification, with an average annual precipitation of 1,300 mm.

Plants were spaced 3.0 m between rows and 0.5 m between plants, resulting in a population density of approximately 6,666 plants per hectare. The cultivar Catuaí was used, and at harvest time, the plants averaged four years in age and 1.9 meters in height.

The prototype used comprised a self-propelled coffee harvester designed for terraced mountain areas (Figure 1). The harvester, mounted on a metal chassis, featured two rubber track wheels, a 15 hp combustion engine, and a 12-liter fuel tank. It also had a telescopic collection system that could be adjusted in height and width to suit different plantation types.

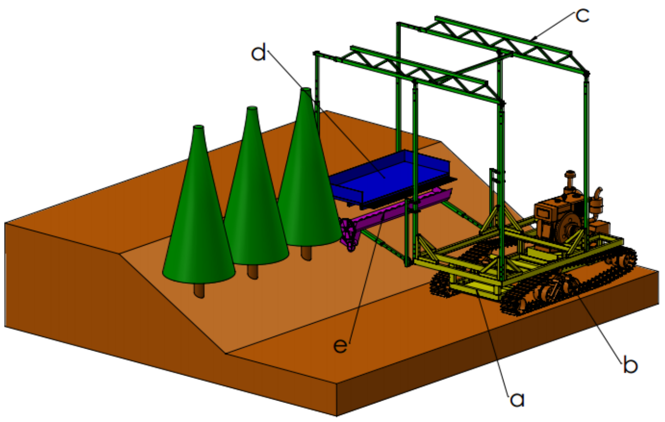

Figure 1. Functional components of the self-propelled harvester tested: a - Structural frame (yellow); b - Propulsion and movement system (orange); c - Regulatory system (green); d - Collection system (blue); e - Discharge system (purple)

The harvesting system consisted of a metal structure covered with metal sheets (Figure 2). This structure featured retractable wooden fingers attached to an elastic tube, providing a 'back and forth' motion. Part 'd' of the prototype is crucial as it surrounds the coffee plant and prevents cherries from falling to the ground during harvesting. The linear movement of the retractable fingers optimizes the process; when the mechanism

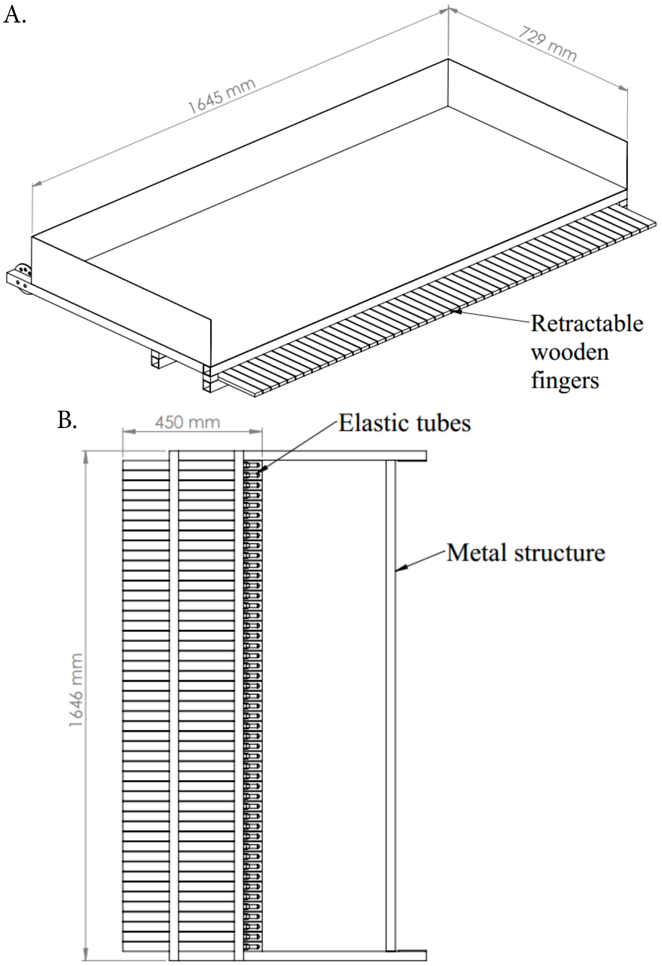

Figure 2. Diagram of the retractable fingers assembly, (A) isometric view, and (B) bottom view

is removed from the plant, the fingers return to their initial position. The component spacing was designed to ensure no cherries pass through. This system is essential for an efficient operation of the prototype.

To quantify losses of uncollected cherries, we used collection cloths during harvest and collection, as proposed by Silva et al. (2013). These cloths were strategically positioned beneath coffee canopy, covering the targeted harvesting zone where fruits are removed. The percentage of cherry loss was then calculated by comparing the mass of cherries captured on the cloths beneath the collection system to the total yield. This calculation is represented by Eq. 1.

$$P_r = \left(\frac{m_p}{m_r + m_p}\right) \times 100 \tag{1}$$

Where:

Pr - the percentage of coffee cherries lost during harvest, %;
mp - the mass of cherries deposited on cloths, kg; and,
mr - the mass of harvested coffee cherries, kg.

Work times were recorded as either productive or auxiliary (Cunha et al., 2016b). Productive time (Tp) is the period during which the machine effectively performs its intended function. Auxiliary time (Ta) refers to the time used for tasks related to the main function, such as maneuvers and adjustments.

Operational efficiency was estimated based on the time the machine effectively performed its designated productive functions relative to the total operation time, including auxiliary tasks. Operational efficiency was calculated as in Eq. 2. Effective operational capacity was calculated as the actual work performed by the machine, considering its efficiency. Operational capacity was determined as in Eq. 3.

$$E_f = \left(\frac{Tp}{Tp + Ta}\right) \tag{2}$$

$$C_{ce} = \left(\frac{LV}{10}\right) E_f \tag{3}$$

Where:

Ef - the operational efficiency, dimensionless;
Tp - the productive time, s;
Ta - the auxiliary time, s;
Cce - the effective field capacity, ha h^{-1};
L - the working width, m; and,
V - working speed, k m h^{-1}.

To compare the self-propelled harvester with manual harvesting, the operational capacity of manual harvesting was also determined using the previously described method. Manual harvesting was conducted by two experienced workers over a total area of 120 m^2, using 40-meter plots covered with jute fabric placed under the coffee canopy. Times for changing the fabric, harvesting, and cleaning were measured for each operation in both treatments. This method allowed determination of the amount of coffee harvested and the total coffee load in hectares per hour.

To assess losses, efficiency, and operational capacity, the prototype traversed the entire experimental plot, harvesting over the collection system. Five terrain inclinations were tested (8°, 17°, 25°, 30°, 38°). The experiment followed a completely randomized design (CRD) with four replicates. Data were analyzed using linear regression, with terrain slope as an explanatory variable. Separate models were fitted for machine and manual harvesting data. The significance of the regression coefficients was tested using the t-test at a 5% probability level. The coefficient of determination (R^2) and the behavior of the studied phenomenon were analyzed for each model.

RESULTS AND DISCUSSION

Table 1 shows the average values of losses in the coffee fruit harvesting process, categorized by the slope of the terraced farmland. Standard deviations (SD) and the coefficient of variation (CV) of the samples are also presented.

The average values of harvesting losses ranged from 6.7 to 11.2%. These losses were due to two main factors: fruits not falling into the collection system and fruits falling into the collector but being lost due to gaps between the retractable fingers. A linear regression analysis yielded a coefficient of determination of 0.08. The t-test indicated that the slope does not correlate with harvesting losses at a $p \leq 0.05$ significance level.

Loureiro et al. (2013) developed a fruit collector for a coffee harvester in sloped areas, achieving loss values between 20 and 22.64% with slopes varying from 0 to 40% (0 to 18°), approximately 2.4 times higher than the losses encountered by the self-propelled harvester's collection system. The collection system developed in this study significantly reduced losses, especially the retractable finger system, which wrapped around the entire base of the plants, preventing fruit escape between the plant and the soil.

Table 2 shows the average operational efficiencies in coffee harvesting using the self-propelled harvester, ranging from 64.1 to 69.9%. The operational capacity of the prototype was calculated based on harvesting times and the worked area (Table 2). The average speed of the self-propelled harvester during the experiment was 1.2 km h^{-1}.

Table 1. Average coffee fruit harvest losses for mechanized harvesting system

Slope (°)	Mean (%)	SD (%)	CV (%)
8	7.0	1.16	16
17	6.7	2.05	30
25	9.8	1.63	16
30	11.2	1.67	15
38	7.2	1.21	17

SD - Standard deviation; CV - Coefficiente of variation

Table 2. Performance of the prototype harvesters in operational capacity and efficiency across varying slopes

Slope (°)	Operational efficiency (%)	Operational capacity (ha h^{-1})
8	67.8	0.10
17	69.9	0.11
25	64.8	0.09
30	64.4	0.09
38	64.1	0.09

Our result for operational efficiency aligns with Cunha et al. (2016b), who established an ideal of 71.94% for mechanized harvesting. Slope and plot size explain variations in this parameter. Steeper slopes hinder harvester movement, increasing harvesting time accident risks. Larger plots require more time and management, impacting efficiency.

A t-test revealed no significant correlation between slope and operational capacity ($p > 0.05$). This finding is crucial for mountain coffee growers battling slope variations on their land. The proposed system maintains efficiency regardless of slope, maximizing productivity for these producers.

Table 3 demonstrates the self-propelled harvester's superior efficiency in mountainous terrain. It outperforms the most common harvesting method, achieving higher operational capacity even with similar labor requirements. This outcome signifies the self-propelled harvester's potential as a more efficient tool for coffee harvesting on terraced mountain farms.

Tavares et al. (2019) demonstrated the clear advantage of mechanized harvesting in steep areas. Their findings show mechanized harvesters achieve operational capacities ten times higher (0.11 ha h^{-1}) compared to manual (0.01 ha h^{-1}) or semi-mechanized methods (0.01 ha h^{-1}). This translates to faster harvesting times, potentially leading to increased productivity and income for coffee producers in mountainous regions.

Our self-propelled harvester achieved an average operational capacity of 0.096 ha h^{-1}, comparable to mechanized harvesting in general and significantly higher than traditional methods (semi-mechanized and manual). This suggests it can be a valuable tool for mountainous coffee farms, harvesting more fruits within less time, increasing yield and farmer income. Furthermore, mechanized harvesting can improve coffee quality by selecting optimally ripe berries, which enhance flavor and aroma due to higher caffeine and phenolic compound content.

Similarly, Souza et al. (2017) used self-propelled harvesters with vibrating rods for stripping, cleaning, and transporting fruits, achieving operational capacities of 0.3 to 0.48 ha h^{-1}. These values are slightly higher because their study was conducted in flat regions. Therefore, our values are still considered acceptable.

Although the self-propelled harvester shows promise, there is still room for improvements in terms of efficiency, adaptability, and safety. Implementing an automated plant embracement system and a more efficient collection system could boost productivity and reduce losses. Additionally, a more robust suspension system, improved traction, and automatic platform height adjustment would broaden its application to steeper and more varied terrain beyond terraced regions. Finally, incorporating a user-friendly control system, improved safety features, and noise reduction would enhance operator ergonomics and safety. We believe these improvements can make the self-propelled harvester an even more effective and safer tool for coffee harvesting in mountainous areas, enhancing sustainability and competitiveness in coffee farming.

Table 3. Operational capacity of a traditional coffee harvesting on a terraced mountain coffee farm

Slope (°)	Operational capacity (ha h-1)
8	0.013
17	0.014
25	0.012
30	0.013
38	0.012

CONCLUSIONS

1. Terrain slope does not significantly affect harvesting losses nor operational capacity.
2. The highest operational capacity was 0.11 ha h^{-1} and achieved at a 17° slope.
3. Average operational efficiency was 66.2%.

Authors' contributions: F.G. Souza was involved in data collection, analysis, implementation of computational simulations, and writing the manuscript. M.M. Teixeira provided valuable guidance as a research advisor, helping to define the research problem and assisting with the construction of the prototype. G.P. Vilibor and M.R.F. Júnior offered guidance on the research objectives and provided feedback on the manuscript, shaping the definitive version. P.R. Cecon provided statistical expertise by assisting with the analysis of the experimental data.

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