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Dimensionless Numbers for Evaluating Mechanization in Agroforestry Systems Based on UN SDG Indicators

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Abstract No agricultural technology can be effective over time unless it is compatible with the natural processes and dynamics of a given agroclimatic region, otherwise, it ultimately becomes unsustainable. Agroforestry Systems (AFS) tend to follow the natural dynamics of forests, but the complexity of their management limits the use of these systems to the manual operational capacity of family farming, which translates into small cultivated areas and arduous labor. Based on the indicators of the Sustainable Development Goals (SDGs) of the United Nations (UN) and through the Dimensional Analysis method, this study sought to establish and test indicators to evaluate and compare the suitability of agricultural machines for AFS cultivated under family farming. Data were collected on three different agricultural machines used in AFS and on two different AFS arrangements, which were compared through the proposed method in order to generate analyses on the suitability of the different machines for the different arrangements. Five indicators were established: π1-energy efficiency; π2-dimensional adaptability; π3-operation over tree rows; π4-productive compaction; and π5-productive–ecological balance. The study demonstrated the effectiveness of the method and the proposed indicators for studying and evaluating the sustainable mechanization of AFS. The results proved that smaller machines are more suitable for use in AFS in the context of family farming. The costal brushcutter was responsible for the best results

when compared with larger machines used in biodiverse and complex systems; however, operator labor-related parameters were not taken into account in this analysis.

Keywords Dimensional analysis, agroforestry systems, agricultural mechanization, family farming, agroecology.

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1. INTRODUCTION

In recent years, Agroforestry Systems (AFS) have stood out as an innovative and sustainable approach to integrating diversified agricultural production and farmer resilience (Tranchina et al. 2024), especially in tropical regions. The growing recognition of the importance of family farming for food security, climate change mitigation and sustainable development has stimulated the search for solutions for food production in environmentally and socially sound ways, thereby strengthening the adoption of AFS (Araya et al. 2023). However, the complexity of implementing and managing these systems means that family farming adopting agroecological practices faces significant challenges (Xavier et al. 2026).

Family farming, although it represents a substantial share of agricultural production in Brazil, already faces relevant obstacles when it comes to conventional mechanization (Albiero et al. 2019), but mechanization within AFS faces specific challenges due to spatial heterogeneity, biodiversity, the presence of trees (Silva et al. 2022) and the physical constraints imposed by the arrangement of the components. The machines available on the market are generally designed for extensive monocultures and do not take into account the complexity of AFS (Morais et al. 2023), which involve intercropped crops and agroecological practices (Altieri 1989). This limits operational efficiency, increases manual labor and physical effort and prevents the scalable adoption of agroforestry practices, especially by small farmers.

Beyond this, the problem that this study seeks to address is the absence of quantitative criteria and indicators that define the ideal dimensional and functional parameters, both for machines operating in AFS and for the AFS arrangements that should accommodate the available machines. These parameters are fundamental for evaluating and comparing the suitability and adaptability between machines and arrangements (Morais et al. 2025), which we refer to as the "machine + AFS" combination. The definition of these criteria is a necessary condition for the mechanization of AFS – the object of study of this work – to be aligned with the Sustainable Development Goals (SDGs) described by the United Nations (UN), and for the formulation of indicators and technical recommendations for the selection, sizing and design of machines and equipment to be adapted to these systems. The SDGs were adopted in 2015 as part of the 2030 Agenda for Sustainable Development and establish a set of social, economic, and environmental targets to be achieved by 2030 (United Nations 2015), making it fundamentally important that the mechanization of sustainable agri-food systems, such as AFS, be in line with their goals.

It is hypothesized that, if dimensionless numbers based on SDG indicators are capable of quantifying, evaluating, and comparing the adaptability, performance, and suitability of agricultural machines in different family-based AFS arrangements, then these dimensionless numbers make it possible to identify the machine + AFS combinations that are most suitable and most aligned with the UN SDGs. This approach is justified because dimensionless numbers bring together, in a few indicators, the combined effect of variables expressed in different units, allowing direct and scale-independent comparisons between different machines and arrangements. In this way, the proposed method offers a technical basis for choosing the best possible machine + AFS combination to maximize productive and energy efficiency and minimize physical and climatic impacts. This procedure can contribute to the mechanization of AFS in accordance with the guidelines of the UN SDGs, reduce the arduousness of manual labor, and thereby increase the operational capacity of the farming family so as to

enable the expansion of areas cultivated with AFS and reforestation. This method can also be used for the planning and prediction of AFS arrangements that are best suited to one or more specific machines.

To test this hypothesis, performance indices were defined based on the indicators of SDGs 2 (Zero Hunger and Sustainable Agriculture), 13 (Climate Action) and 15 (Life on Land) (United Nations 2015; Ji and Lee 2021; Morais et al. 2023; Jung and Vendrametto 2025; Gonçalves et al. 2025), and the input variables were defined to compose these indices. The indices were transformed into dimensionless numbers through the Dimensional Analysis method (Murphy 1950; Langhaar 1951; Taylor 1974; Back 1983; Albiero et al. 2011; Robinett 2015; Manoel et al. 2024; Morais et al. 2025). An interpretation of these dimensionless numbers was developed to describe their applicability and their correlations with the SDGs. To test the robustness and applicability of the dimensionless numbers, data were collected from the literature regarding three different agricultural machines used in AFS (Morais 2022; Morais et al. 2023, 2025) and data on the arrangement and productivity of two of these systems (Silva et al. 2018; Comolli et al. 2024). For the purposes of this study, these machines were considered to operate in these systems so as to generate six treatments (machine + AFS combinations). Finally, as part of the Dimensional Analysis method, dimensionless graphs were constructed to support the evaluation and comparison of the treatments.

The main objective of this study was to formulate and test dimensionless numbers, also called "*π-terms*", based on the indicators of SDGs 2, 13 and 15, in order to quantify, evaluate and compare the performance, adaptability and suitability of agricultural machines in different AFS contexts. Specifically, the objectives were: (i) to define indices and π-terms that integrate indicators of adaptability, productivity, emissions and environmental conservation; (ii) to calculate π-terms for the machine + AFS combinations (treatments) found in the literature and identify binomials with strong correlation; (iii) to construct dimensionless graphs to interpret the relationships established by the treatments; and (iv) to propose a ranking of the treatments in order to provide technical support for the selection and design of machines and equipment for AFS.

2. MATERIALS AND METHODS

2.1 Definition of the variables

The input variables that characterize and describe the study phenomenon were defined, that is, the variables describing the characteristics of agricultural machinery and AFS. These variables served as the basis for defining the adaptability, performance, and sustainability indices of mechanization in family-based AFS, based on SDG indicators. The variables describing the characteristics of the machines considered in this study are 12: machine fuel consumption (L/h), emission factor (kg CO_2/L), machine power (kW), operating time (h), machine speed (km/h), machine width (m), operating width (m), tire/track traffic area (m²), number of machine passes, traffic lane width (m), machine weight (kg), and tire/track contact area (m²).

The variables describing the characteristics of the AFS considered in this study are 10: total production (kg), total agricultural area (ha), trafficable width (m), total inter-row length (m), total tree weight (kg), individual tree weight (kg), diameter at breast height (m), Odum index, number of individuals and number of species. Table 1 presents the variables according to the group they describe, together with their respective symbols and units of measurement.

Table 1 Variables, symbols, and units used to characterize agricultural machinery operations in agroforestry systems (AFS).

Group	Variable	Symbol	Unit
Machinery	Machine fuel consumption	C	L/h
	Emission factor	F	kg CO_2/L
	Machine power	Pow	kW
	Operating time	T	h
	Machine speed	Spe	km/h
	Machine width	MWi	m
	Operating width	OWi	m
	Tire/track traffic area	TTA	m²
	Number of machine passes	NMP	–
	Traffic lane width	TLW	m
	Machine weight	MWe	kg
	Tire/track contact area	TCA	m²
AFS	Total production	TP	kg
	Total agricultural area	TA	ha
	Trafficable width	TW	m
	Total inter-row length	TIL	m
	Total tree weight	TTW	kg
	Individual tree weight	ITW	kg
	Diameter at breast height	DBH	m

Odum index	Odum	–
Number of individuals	N	–
Number of species	S	–

2.2 Definition of the indices based on the SDGs

The objective of this stage is to define adaptability, performance, and sustainability indices, using the variables previously described, that reflect the operational impacts of machinery in AFSs, in agreement with the SDG indicators. These indices served as the basis for defining the dimensionless terms and, therefore, must have defined units.

According to the literature, the mechanization of AFS managed under family farming can contribute to achieving the objectives of SDG 2 (Zero Hunger and Sustainable Agriculture), 13 (Climate Action), and 15 (Life on Land) (United Nations 2015; Ji and Lee 2021; Morais et al. 2023; Jung and Vendrametto 2025; Gonçalves et al. 2025). For each of these SDGs, the indicators that may be directly affected by the technification of these agricultural systems were selected. To evaluate the contribution of AFS mechanization to achieving the targets of these indicators, agricultural machinery adaptability indices were identified that can measure and compare machine operation and the results of the introduction of mechanization into AFS cultivated under family farming.

The agricultural productivity index (AP) was selected in relation to SDG 2; the hourly greenhouse gas emissions (HGE) and traversal efficiency (TE) indices were selected in relation to SDG 13; and the passage margin (PM), operational coverage (OC), traffic-free area (TFA), soil compaction (SC), and areal density of diverse forest biomass (DFB) indices were selected in relation to SDG 15. Table 2 presents the selected indicator indices of adaptability, performance and sustainability, the SDG to which they are related and a brief summary of the description and justification of this relationship.

Table 2 SDG-related indicator indices of agroforestry mechanization, units and their description. Abbreviations: AP (agricultural productivity), HGE (hourly greenhouse gas emissions), TE (traversal efficiency), PM (passage margin), OC (operational coverage), TFA (traffic-free area), SC (soil compaction), DFB (areal density of diverse forest biomass), SDG (Sustainable Development Goal), AFS (agroforestry system).

Index	SDG	Unit	Description
AP	2	kg/ha	Measures agricultural productivity, that is, the productive efficiency of AFS for food security.
HGE	13	kg/h	Quantifies the hourly greenhouse gas (GHG) emissions generated during machine operation, that is, it assesses the climatic impact of mechanized operation.
TE	13	W/m	Represents power per distance, that is, the energy required to perform traversal during operation, making it possible to identify machines that cover greater distances with lower power demand, as well as situations of energy waste.

PM	15	m	Calculated from the difference between inter-row width and machine width, that is, it measures the dimensional compatibility of machines within the AFS, enabling tree-based systems.
OC	15	m	Defined by the difference between effective operating width and machine width, it measures expanded operational capacity, that is, the machine's ability to operate beyond its physical width and, consequently, reduce the number of passes.
TFA	15	m²	Calculated from the difference between total area and the area trafficked by machines, it represents the traffic-free area. Higher values indicate larger tree-covered and conserved areas.
SC	15	kg/m²	Determines the potential for soil compaction based on the ratio between machine weight and tire/track contact area, that is, it assesses pressure on the soil, which compromises ecosystem integrity.
DFB	15	kg/ha	Expresses the areal density of diverse forest biomass, calculated from tree weight and diversity richness observed within the total area, that is, it reflects AFS robustness, indicating conservation and regeneration capacity.

Detailed descriptions and interpretations of each index, including the SDG indicators covered by the indices and the way they are calculated are provided in the Supplementary Material (Morais et al. 2026) under the link <https://doi.org/10.25824/redu/HZJORV>.

2.3 Definition of the dimensionless numbers

The eight (8) steps, briefly presented below and described in detail in the Supplementary Material (Morais et al. 2026) under the link <https://doi.org/10.25824/redu/HZJORV>, describe the Dimensional Analysis method for defining the dimensionless numbers – also known and referred to in this study as "pi-terms" or "π-terms" – and constructing the dimensionless graphs (Murphy 1950; Langhaar 1951; Taylor 1974; Haynes 1975; Back 1983; Maciel 1993; Albiero et al. 2011; Legendre and Legendre 2012; Robinett 2015; Freitas et al. 2016; Fengler 2018; Manoel 2020; Manoel et al. 2024; Morais et al. 2025). The objective here is to establish π-terms to compare the adaptability and performance of agricultural machines in different AFS contexts. The π-terms will serve as the basis for describing and analyzing the study phenomenon: the mechanization of agroforestry tasks, that is, machines entering and operating in AFS.

The method was applied in eight steps: (1) prior standardization of the indices in the International System of Units (SI); (2) decomposition of the index units into the basic dimensions mass (M), length (L), and time (T); (3) construction of the dimensional matrix with the exponents of each index; (4) selection and verification of a three-dimensional reference subspace representative of the phenomenon under study (here, K6, K7, and K8) and testing of its characteristic (determinant $\neq 0$); (5) formulation and solution of the homogeneous linear system under the condition of dimensionlessness (sum of the exponents equal to zero for M, L, and T) and writing of the three corresponding equations; (6) solution of this system, obtaining the solution matrix and definition of the π-

terms; (7) calculation of the π-terms for each treatment and construction of the correlation matrix to identify the relevant binomials; and (8) preparation of the dimensionless graphs from the binomials with strong correlation ($|r| > 0.7$).

2.4 Interpretation and applicability of the π-terms

Each π-term was formulated to capture a specific dimension of the adaptability and performance of agricultural machines in AFS and family farming, integrating operational, environmental, and sustainable management aspects in accordance with the UN SDGs. The nomenclature and clear definition of each π-term facilitate managers' understanding of the critical points, ranging from environmental impact and operational performance to soil conservation and the contribution to agroecosystem sustainability. These π-terms can be used to compare different machines and to guide investments in technologies better adapted to AFS.

This structure provides a global analysis of the factors involved and allows an integrated and dimensionless assessment of agricultural systems in relation to the SDG indicators. The interpretation of each π-term is presented below through the description of the objectives and applicability of each one.

π1 – Dimensionless number of Energy Efficiency – Costa Number[1]

$$\pi 1 = \frac{TE * AP^2 * TFA^{3/2}}{HGE^3}$$

π1 integrates traversal efficiency (TE) with agricultural productivity (AP) and traffic-free area (TFA), in relation to hourly GHG emissions (HGE). The objective of this π-term is *to assess the energy efficiency of the "machine + AFS" system in relation to gas emissions*, as measured by its ability to convert the available energy into useful outcomes: productivity and preservation with low gas emissions.

In practical terms, π1 measures the adequacy of the power used to drive or pull implements and to perform traversal during operation, that is, how much of the energy resource is converted into productivity and conservation with the least possible waste. Thus, this π-term makes it possible to compare the energy efficiency of machines by considering the TE – the relationship between power and its derived variables: speed and operating time – most suitable for a given AFS arrangement, to maximize productivity in preserved areas and minimize emissions. The HGE intrinsic to the phenomenon under study is considered a deleterious element in π1.

As TE generally tends to increase with higher power levels, and because TE appears in the numerator of π1, an isolated increase in power tends to raise π1 values at first. However, higher power levels are usually accompanied by higher gas emissions (HGE) – although modernization and operating mode may influence this

[1] Prof. Dr. Manoel Baltasar Baptista da Costa, a pioneer of agroecology in Brazil, worked at the intersection of agroecology, family farming, agrarian reform and agricultural sustainability. His name is associated with π1 because this term synthesizes productive and energy efficiency within a low-input, context-appropriate perspective.

relationship (Mantoam et al. 2016; Pascuzzi et al. 2024; Martins et al. 2025). Since HGE is amplified by the exponent 3 in the denominator of π1, small increases in HGE may suppress the positive effect of the numerator and, therefore, reduce the value of π1. In other words, excessive power without a proportional gain in productivity represents energy waste and worsens the energy efficiency of the system, generating more pollution.

To illustrate, consider two machines traveling the same distance: machine "A" with lower power and machine "B" with higher power. If "A" emits fewer gases than "B", then, even if "B" presents a numerically higher TE, the cubic HGE term in the denominator strongly penalizes "B"; thus, the π1 of "A" should be higher than that of "B," because the lower emission intensity of "A" greatly reduces the denominator and increases the dimensionless value.

In this π-term, the AP index is squared, which demonstrates the emphasis placed on productivity (which, like the TFA index, is in the numerator of the equation) in the assessment of machine power. In practice, larger and more powerful machines may increase productivity, but this often occurs at the cost of greater operational limitation in preserved areas (since wide machines cannot enter narrow inter-rows) and higher consumption/emissions.

In summary, high π1 values are desirable because they reflect scenarios in which energy efficiency is greater, that is, they indicate that the available power is being well utilized in terms of production and preservation with low emissions; low values signal energy waste or incompatibility between the machine and the AFS arrangement. In this way, π1 guides the selection of suitable power classes for AFS and family farming.

π2 – Dimensionless number of Dimensional Adaptability – Caporal Number[2]

$$\pi 2 = \frac{PM}{TFA^{1/2}}$$

π2 assesses the physical compatibility of the machine to travel through the inter-rows (PM) as a function of the restricted traffic space within the total area (TFA) due to the presence of trees. The objective of this π-term is *to assess the dimensional adaptability of the machine* to the AFS in question, according to its design and structure. This π-term can be used to compare the dimensional adaptability of machines according to the structural design of AFS, thereby guiding the selection of better-adapted technologies. Higher values indicate that the machine has a good passage margin relative to the preserved area, making it more compatible with AFS, which suggests that it is suitable for operating without damaging the trees and contributes to ecosystem conservation. Lower values suggest that the passage margin is reduced in comparison with the protected space, increasing the risk of interference with the vegetation and, consequently, of damage to the ecosystem.

[2] Prof. Dr. Francisco Roberto Caporal, one of the leading pioneers of agroecology in Brazil and Latin America, was a major reference in agroecological rural extension and in the co-construction of knowledge with farmers. He is honored in π2 because this term reflects adaptation of technology to the concrete conditions of family farming and agroecosystems.

250

251 π3 – Dimensionless number of Operation over Tree Rows – Costa Number[3]

252 $$\pi\ 3 = \frac{OC}{TFA^{1/2}}$$

253

254 π3 measures the ability of the machine to expand its area of operation (OC) as a function of the tree-
255 covered area, where traffic is restricted (TFA). The objective of this π-term is *to assess the machine's ability to*
256 *operate over tree rows* and it can be applied to compare the operational extension capability of machines that travel
257 through the inter-rows of an AFS, indicating the equipment that can operate directly over tree-covered areas
258 without the need to travel over them. Higher values indicate that the machine can expand its area of operation over
259 tree-covered areas, which contributes to the mechanization of tasks in areas with greater tree density and the
260 consequent reduction of manual labor. Lower values suggest that the machine has little or no ability to operate on
261 tree rows, requiring more movement within the inter-rows.

262 This π-term is fundamental for machines that operate specifically beyond their own limits, such as
263 sprayers, input applicators, forage harvesters, pruners, etc., and less useful for machines that operate locally, such
264 as soil tillers, planters, etc.

265

266 π4 – Dimensionless number of Productive Compaction – Primavesi Number[4]

267 $$\pi\ 4 = \frac{SC}{AP}$$

268

269 π4 measures the soil compaction potential generated by the machine (SC) as a function of the
270 productivity observed in the AFS (AP). The objective of π4 is *to assess the pressure exerted on the soil for each*
271 *unit of production obtained*. This π-term can be used to compare the ability of machines to achieve high
272 productivity indices with lower physical impact on the soil. It can be applied to demonstrate operational efficiency
273 by relating the production obtained to the physical impact generated on the soil, thereby guiding the selection of
274 more suitable technologies that minimize the pressure exerted on the soil without compromising productivity.

275 Higher values indicate that the machine exerts high pressure on the soil and generates high
276 compaction to achieve the observed production. This suggests a negative environmental impact, in which
277 mechanized management may compromise soil health. Lower values suggest that the pressure exerted on the soil
278 is relatively low in relation to productivity, resulting in an operation with lower compaction. This scenario is

[3] Prof. Dr. Adilson Dias Paschoal, a precursor of organic agriculture in Brazil, became a landmark voice against agrotoxics and in favor of ecologically balanced farming. His name is linked to π3 because this term values productive intervention with lower direct impact on tree-covered areas and the agroecosystem.

[4] Agronomist Ana Maria Primavesi, a foundational figure in Brazilian agroecology, transformed the understanding of soil as a living system and advanced ecological soil management. She is the natural honoree of π4, which directly addresses soil compaction and soil physical quality.

desirable, as it indicates that the machine can maintain the soil under better conditions, favoring the sustainability of the AFS while also generating high productivity indices.

π5 – Dimensionless number of Productive–Ecological Balance – Mendes Number[5]

$$\pi 5 = \frac{DFB}{AP}$$

π5 expresses the ecological robustness of an AFS through the areal density of diverse forest biomass (DFB) in relation to agricultural productivity (AP). This index represents the influence of productivity on the forest composition and conservation of the system. The objective of this π-term is *to assess the capacity of mechanized management to balance productivity with forest biodiversity*. π5 can be applied to compare the capacity of mechanized AFS to reconcile agricultural production with environmental conservation, thereby demonstrating the capacity of mechanized AFS to sustain both production and environmental conservation. The π-term in question quantifies the ecological performance of productive systems, helping managers identify the most sustainable ones and promote the integration of efficient production with environmental conservation.

Higher values indicate that, for each unit of agricultural production, there is abundant and diverse forest biomass, suggesting a robust AFS with high regenerative potential, greater environmental preservation, and greater capacity for environmental conservation and regeneration, especially when its agricultural productivity is high. Lower values suggest that the system is primarily oriented toward agricultural production, which overrides environmental preservation, indicating lower biodiversity and regeneration capacity.

2.5 Correlation of the dimensionless numbers with the UN SDGs

The integration of dimensionless models (π-terms) with the Sustainable Development Goals (SDGs) gives the π-terms a logical foundation grounded in globally recognized agendas and is essential for aligning theoretical results with practical sustainability targets. By defining the π-terms from indices that reflect operational and environmental characteristics of agricultural machines, we are using variables selected on the basis of specific SDG indicators. This correlation facilitates the interpretation and analysis of the π-terms by managers and decision-makers and makes it possible to clearly identify how each aspect of the operation – from productive efficiency to ecosystem conservation – contributes to the global goals of food security, climate change mitigation and protection of life on land.

In addition, several other benefits essential to the robustness of these dimensionless models can be observed when each π-term is correlated with one or more specific SDGs, such as: (i) clarity and communication: the results become more understandable to managers, allowing the immediate identification of the sustainability

[5] Francisco Alves Mendes Filho (Chico Mendes), a rubber tapper, union leader and environmental activist, became an enduring symbol of forest conservation and the defense of traditional peoples. He is honored in π5 because this term expresses the balance between production and ecological integrity in tree-based systems.

aspects addressed; (ii) policy guidance: this makes it possible to create specific guidelines and interventions to improve performance in critical areas, such as emission reduction or ecosystem conservation; and (iii) integration of dimensions: by incorporating operational variables (power, speed, productivity, etc.) and environmental variables (traffic-free area, forest biomass, diversity, etc.) that reflect the SDG indicators, the π-terms become powerful instruments for evaluating the efficiency of agricultural machines in the context of AFS and family farming.

The explicit characterization of the π-terms in relation to SDGs 2, 13, and 15 makes it possible to clearly identify which strengths and weaknesses of agroforestry mechanization are associated with productivity, climate mitigation, and environmental conservation. In this context, π1 and π4 are oriented toward operational efficiency and climatic impact, whereas π2, π3, and π5 focus on the structural adaptation of machines to AFS and on the preservation of productive ecosystems. This organization enables a rapid understanding of how each π-term contributes to these different aspects, thereby guiding actions to improve productive performance, reduce impacts, and strengthen environmental protection.

Table 3 presents this correlation by showing the π-terms, their names, formulas, the SDGs to which they are related, what would be the ideal or desirable behavior of their values (serving as a reference for comparing the adaptability and performance of agricultural machines in different AFS contexts) and a brief summary and justification of this relationship.

Table 3 Proposed indicator π-terms, their names, formulas, relationships with the SDGs, expected behaviors, and brief description and justification. Abbreviations: AP (agricultural productivity), HGE (hourly greenhouse gas emissions), TE (traversal efficiency), PM (passage margin), OC (operational coverage), TFA (traffic-free area), SC (soil compaction), DFB (areal density of diverse forest biomass), SDG (Sustainable Development Goal), AFS (agroforestry system).

π-term	**Name**	**Formula**	**SDG**	**Behavior**
π1	Dimensionless Number of Energy Efficiency	$\frac{TE * AP^2 * TFA^{3/2}}{HGE^3}$	2, 13 and 15	Higher values are ideal.
Description and justification	Assesses the energy efficiency of the "machine + AFS" system. High values reflect scenarios in which the available power is adequate to increase productivity (SDG 2) in preserved areas (SDG 15) at low environmental cost (SDG 13).			
π2	Dimensionless Number of Dimensional Adaptability	$\frac{PM}{TFA^{1/2}}$	15	Higher values are ideal.
Description and justification	Denotes the dimensional compatibility of the machine with preserved areas by comparing passage margin with protected area. High values indicate excellent dimensional adaptability and preservation of tree-covered areas (SDG 15).			
π3	Dimensionless Number of Operation over Tree Rows	$\frac{OC}{TFA^{1/2}}$	13 and 15	Higher values are ideal.

Description and justification	Measures the ability to operate over tree rows without direct traffic (operating reach / protected area). High values indicate efficient operations in tree-covered and dense areas (SDG 15) and a reduction in the number of passes and the resulting emissions (SDG 13).			
$\pi 4$	Dimensionless Number of Productive Compaction	$\frac{SC}{AP}$	2 and 15	Lower values are ideal.
Description and justification	Assesses the relationship between soil compaction and agricultural productivity by quantifying the pressure exerted on the soil per unit of production. Low values mean less compaction per unit of production, promoting healthy soil (SDG 15) and efficient productivity (SDG 2).			
$\pi 5$	Dimensionless Number of Productive–Ecological Balance	$\frac{DFB}{AP}$	2 and 15	Higher values are ideal.
Description and justification	Measures the balance between environmental conservation and productivity. High values indicate robust AFS, with high ecological contribution (diverse forest biomass) and regenerative capacity (SDG 15), together with satisfactory productivity (SDG 2).			

2.6 Data collection and experimental design

To evaluate the performance and adaptability of mechanization in agroecological AFS through the proposed dimensionless numbers, data on the variables required to calculate the π-terms were collected. Data collection was based on data published in the literature, specifically studies providing the data for the variables defined in item 2.1 of this study. Priority was given to studies that described and evaluated agricultural machines for AFS, machines for family farming, agroforestry systems, agroecosystems and biodiverse production systems.

To achieve the objectives of this study, 58 scientific studies were initially analyzed, of which 5 were selected as the main basis for composing the dataset. Data referring to the agricultural machine variables were obtained from three studies (Morais 2022; Morais et al. 2023, 2025), in which three distinct machines intended for managing the biomass produced in the inter-rows of agroecological AFS were evaluated. Data related to the AFS variables were extracted from two studies (Silva et al. 2018; Comolli et al. 2024) to characterize two distinct AFS arrangements. For the purposes of analysis, it was considered that the machines evaluated were employed in the AFS described in the literature according to their respective structural arrangements, making it possible to compare the π-term values resulting from the "machine + AFS" interaction. This combination of 3 machines and 2 AFS arrangements resulted in 6 treatments.

AFS1 was defined as the set of variable data obtained from Comolli et al. (2024) and AFS2 as the set whose variables were extracted from Silva et al. (2018). Regarding the machines, RBC corresponds to the tractor-mounted rotary brushcutter, CBC refers to the costal brushcutter and GRM refers to the mini grain reaper machine. From the combination of these factors, six treatments were defined, namely: 1: AFS1 + RBC; 2: AFS1 + CBC; 3: AFS1 + GRM; 4: AFS2 + RBC; 5: AFS2 + CBC; and 6: AFS2 + GRM.

Some data were explicitly reported in the studies, whereas others had to be calculated, as described below. AFS1: the variable "DBH" was obtained from the mean of the values presented in "Table 2" of that study, referring to year 12 (2022); "N" is the result of summing the 7,400 trees and the 3,700 yerba mate individuals (*Ilex paraguariensis*) per hectare; "TIL" was calculated considering a square area of 10ha and the distance between

inter-rows; “TP” was based on the 20kg of yerba mate produced per plant in AFS in Argentina (Eibl et al. 2000). AFS2: “TP” was calculated by summing the mean yields of each product, considering only the years in which production occurred and assuming a weight of 10kg per watermelon unit (*Citrullus lanatus*), 25kg per banana bunch (*Musa spp.*) and 560kg per m³ of African mahogany wood (*Khaya ivorensis*); “N” was obtained by multiplying the total number of trees per hectare by 8ha; “TW” was obtained by subtracting 0.5m of tree-row bed, on both the left and right sides, from the total inter-row width (3m); “TIL” was calculated as described above, but considering a total area of 8ha.

With regard to the machines, the variables that had to be calculated are described below. RBC: “MWe” was obtained by summing the weights of the tractor and the implement. CBC: “TLW” and “TCA” were calculated based on the operator’s footwear dimensions, since this machine operates while being carried on the operator’s shoulders. For all machines: “NMP” was calculated proportionally for the “TW” of AFS1 and AFS2 based on the NMP observed by the authors for a “TW” of 6 m; “T” was obtained by multiplying the operating time (h/ha) by the total trafficable area (ha), which, in turn, was obtained by multiplying “TW” by “TIL”.

Table 4 presents the variable data obtained from the literature and used in this study.

Table 4 Collected data for the machinery and AFS variables used in the six treatments. Data sources: (Silva et al. 2018; Morais 2022; Morais et al. 2023, 2025; Comolli et al. 2024). Abbreviations: C (machine fuel consumption), F (emission factor), Pow (machine power), T (operating time), Spe (machine speed), MWi (machine width), OWi (operating width), TTA (tire/track traffic area), NMP (number of machine passes), TLW (traffic lane width), MWe (machine weight), TCA (tire/track contact area), TP (total production), TA (total agricultural area), TW (trafficable width), TIL (total inter-row length), TTW (total tree weight), ITW (individual tree weight), DBH (diameter at breast height), Odum (Odum index), N (number of individuals), S (number of species), AFS (agroforestry system).

			Treatments					
Group	Variable	Unit	1	2	3	4	5	6
Machines	C	L/h	7,13	1,16	1,36	7,13	1,16	1,36
	F	kg.CO_2/L	3,1	2,8	2,8	3,1	2,8	2,8
	Pow	kW	36,8	1,5	6,6	36,8	1,5	6,6
	T	h	17,6	62,6	24,4	28,2	100,2	39,0
	Spe	km/h	1,7	0,5	2,4	1,7	0,5	2,4
	MWi	m	1,5	0,35	1	1,5	0,35	1
	OWi	m	1,3	2	1,2	1,3	2	1,2
	TTA	m²	16666,5	6666,6	24444,2	26667	10666,8	39111,6
	NMP	-	2,5	2,0	5,0	1,7	1,3	3,3
	TLW	m	0,6	0,3	0,44	0,6	0,3	0,44
	MWe	kg	2392	14	120	2392	14	120
	TCA	m²	0,136	0,045	0,0528	0,136	0,045	0,0528
AFS	TP	kg	740000	740000	740000	381312	381312	381312
	TA	ha	10	10	10	8	8	8

TW	m	3	3	3	2	2	2
TIL	m	11111	11111	11111	26667	26667	26667
TTW	kg	17463420	17463420	17463420	2750460	2750460	2750460
ITW	kg	393	393	393	313	313	313
DBH	m	0,25	0,25	0,25	0,23	0,23	0,23
Odum	-	0,934	0,934	0,934	0,440	0,440	0,440
N	-	44410	44410	44410	8800	8800	8800
S	-	10	10	10	4	4	4

381

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3. RESULTS

Tables 5, 6, and 7 below present, respectively, the results of the index calculations with the units already expressed in MLT, the results of the π-term calculations and the correlation matrix of the latter for identifying the binomials with strong correlation.

Table 5 Results of the SDG-related indices calculations. Abbreviations: AP (agricultural productivity), HGE (hourly greenhouse gas emissions), TE (traversal efficiency), PM (passage margin), OC (operational coverage), TFA (traffic-free area), SC (soil compaction), DFB (areal density of diverse forest biomass), SDG (Sustainable Development Goal).

Treatment	AP	HGE	TE	PM	OC	TFA	SC	DFB
	(kg/m²)	(kg/s)	(kg.m/s³)	(m)	(m)	(m²)	(kg/m²)	(kg/m²)
1	7,40	0,0061	1,208	1,50	-0,20	83333,5	17588,24	163,19
2	7,40	0,0009	0,045	2,65	1,65	93333,4	311,11	163,19
3	7,40	0,0011	0,112	2,00	0,20	75555,8	2272,73	163,19
4	4,77	0,0061	0,755	0,50	-0,20	53333,0	17588,24	15,14
5	4,77	0,0009	0,028	1,65	1,65	69333,2	311,11	15,14
6	4,77	0,0011	0,070	1,00	0,20	40888,4	2272,73	15,14

Table 6 Results of the π-term calculations.

Treatment	π1	π2	π3	π4	π5
1	6,88E+15	0,0052	-0,00069	2376,79	22,05
2	9,49E+16	0,0087	0,00540	42,04	22,05
3	1,08E+17	0,0073	0,00073	307,13	22,05
4	9,13E+14	0,0022	-0,00087	3690,05	3,18
5	1,58E+16	0,0063	0,00627	65,27	3,18
6	1,11E+16	0,0049	0,00099	476,82	3,18

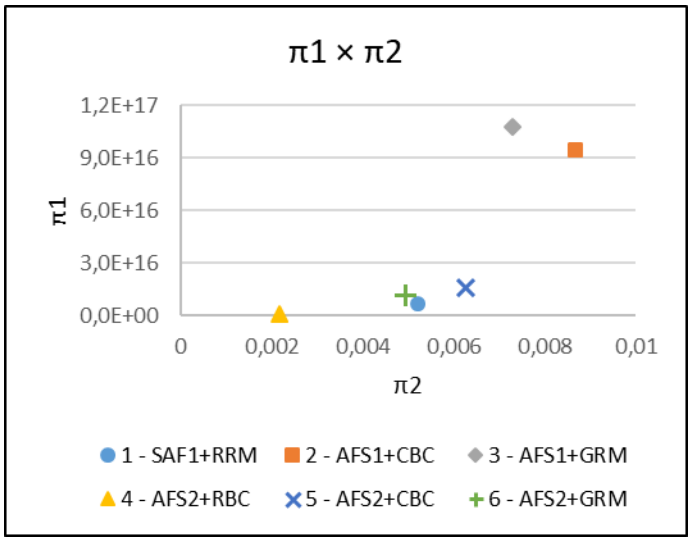
Table 7 Correlation matrix of the π-terms showing strong correlation coefficients for binomials π1 × π2, π4 × π2 and π4 × π3.

	π1	π2	π3	π4	π5
π1	1,00	-	-	-	-
π2	0,80	1,00	-	-	-
π3	0,30	0,66	1,00	-	-
π4	-0,58	-0,85	-0,73	1,00	-
π5	0,69	0,63	-0,06	-0,18	1,00

The binomials that show strong correlation coefficients, according to Schober and Schwarte (2018), greater than 0.70 and less than -0.70, are: π1 × π2 (0.80), π4 × π2 (-0.85), and π4 × π3 (-0.73). The dimensionless graphs generated from each of these three binomials explain the study phenomenon through the representation of the relationships between π-terms (Albiero et al. 2011), with the purpose of evaluating and comparing the adaptability of mechanization in AFS. In interpretive terms, higher values are desirable for all π-terms except π4, whose meaning (compaction per unit of production) makes lower values preferable, given the negative impacts of traffic and intensive machine use that have already been widely documented, as discussed by Becker et al. (2022). Thus, for the π1, π2, and π3 axes, points located higher and farther to the right indicate greater adaptability and performance of a given machine for a specific AFS; for the π4 axis, by contrast, the lowest points represent this. Each point (symbol) in the graph represents a treatment (a specific machine + AFS combination).

The dimensionless graph π1 × π2 (Figure 1) represents the relationship between the energy efficiency of the mechanized operation (π1) and the dimensional adaptability of the machine to the agroforestry system (π2). The strong positive correlation of this binomial shows that machines that are better dimensionally adapted to AFS also tend to exhibit higher energy efficiency in the sample set, which is consistent with the evidence presented by Morais et al. (2025) that the selection of machines suited to the operating conditions can reduce working time and fuel consumption, thereby increasing operational efficiency.

Figure 1 Dimensionless graph for the binomial π1 × π2. Higher and farther-right points indicate better combined energy efficiency and dimensional adaptability; treatments 2 and 3 showed the best performance.



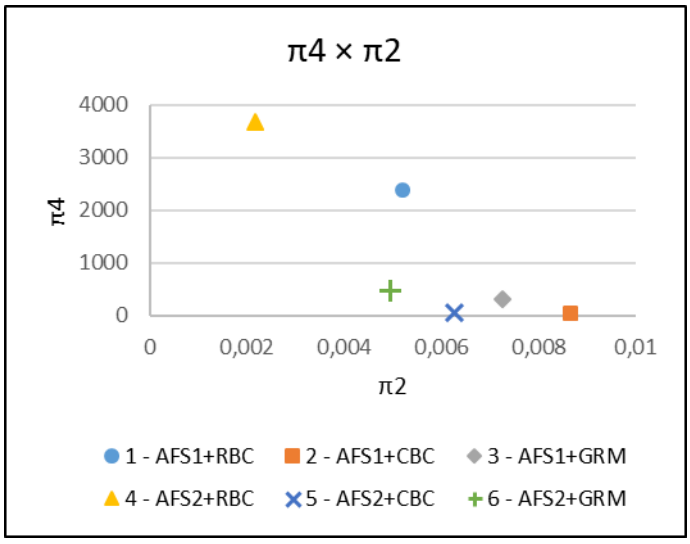
Reading the graph makes it possible to identify treatments that more efficiently convert energy into agricultural productivity and environmental preservation, and the suitability of the size of these machines to the AFS arrangement is essential, which is also demonstrated in this graph. This pattern is consistent with the understanding of Yan et al. (2024) that the efficiency of mechanized operation depends both on power and on the geometric suitability between the machine and the space available in the cropping system. It should be noted, however, that Mantoam et al. (2016) demonstrated that more powerful tractors have lower energy demand and

lower GHG emissions; however, in the context of the AFS evaluated here, possible energy gains may be neutralized when greater power implies width/size incompatible with the inter-rows, since HGE is calculated here directly from the machine's fuel consumption. This behavior is observed in the graph by the points allocated farther to the right and higher up, representing the higher values of both π-terms.

From this perspective, treatments 2 and 3 showed the best results, with the GRM being more energy-efficient and the CBC being more dimensionally adaptable. The smaller size of the CBC, in line with the observations of Daum (2023) that smaller machines tend to reduce the intensity of the labor required, made treatment 5 the third most suitable compared with the others, making the CBC the most suitable machine for the different AFS arrangements in this study and in relation to what this graph demonstrates.

The dimensionless graph π4 × π2 (Figure 2) represents the relationship between the soil compaction potential exerted by the machine (π4) and its dimensional adaptability to the agroforestry system (π2). The strong negative correlation of this binomial indicates that better dimensional adaptability is strongly associated with lower compaction per unit of production, a fact demonstrated by Zhang et al. (2024), who highlight that the proper selection of the type of agricultural machinery is essential to reduce compaction, ensure sustainable production systems and restore productivity in compacted soils.

Figure 2 Dimensionless graph for the binomial π4 × π2. Farther-right and lower points indicate better dimensional adaptability with lower soil compaction; treatments 2 and 3 showed the best performance.



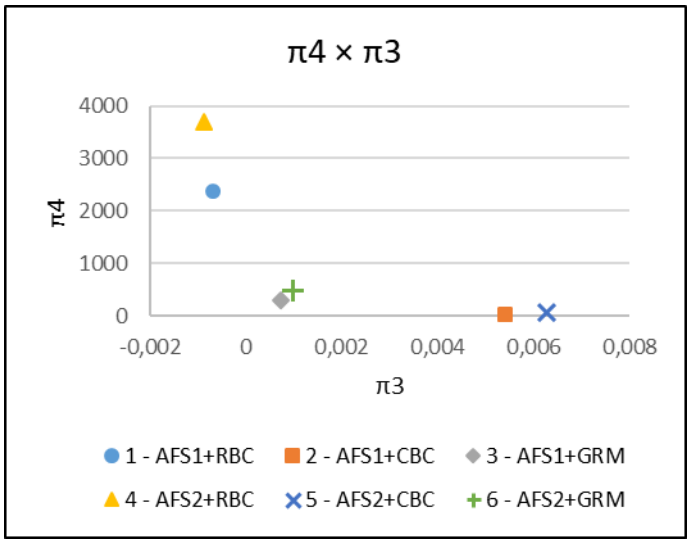
Reading the graph makes it possible to identify treatments that reconcile greater dimensional adaptability of the machines to the AFS arrangement with lower soil compaction, highlighting the importance of machine size and geometry in reducing physical impacts on the soil, which is in agreement with the results observed by Parvin et al. (2022), who show that increasing machine size tends to intensify compaction and reduce crop productivity. This behavior is observed in the graph by the points positioned farther to the right and lower down, representing higher π2 values and lower π4 values. From this perspective, treatments 2 and 3 again showed

the best results, with the CBC being the machine with the lowest compaction potential and the greatest dimensional adaptability, which is in line with Cambi et al. (2015), who highlight the relevance of vehicle weight, dimensions, and contact pressure in determining the severity of soil compaction.

The smaller size and weight of the CBC also contributed to the good performance of treatment 5, reinforcing that more compact machines tend to present better structural adaptation to AFS and lower compaction potential, in line with the evidence observed by Keller and Or (2022), in which heavier and larger vehicles increase the risk of deep compaction and degradation of the physical properties of the soil, while, according to Marques Filho et al. (2024), lighter machines exert less pressure, reduce the physical degradation of the soil, and preserve its functional quality. This makes the CBC the most suitable machine among the arrangements evaluated in this study, in light of the behavior expressed by this graph.

The dimensionless graph π4 × π3 (Figure 3) represents the relationship between the soil compaction potential exerted by the machine (π4) and the machine's ability to operate over tree rows (π3). The strong negative correlation of this binomial suggests that machines with lateral operating capacity tend to reduce compaction, possibly because they expand the coverage of the intervention in each pass and, consequently, reduce the total number of passes (NMP). This interpretation is supported by studies such as Wang et al. (2022), which show that NMP is directly related to variations in soil density and penetration resistance, both indicators of compaction, with increasing effects as the number of passes accumulates.

Figure 3 Dimensionless graph for the binomial π4 × π3. Farther-right and lower points indicate greater capacity to operate over tree rows with lower soil compaction; treatments 2 and 5 showed the best performance.



Reading the graph makes it possible to identify treatments that reconcile greater machine capacity to operate over tree rows with lower soil compaction, highlighting the importance of machines that expand their operating width without increasing the physical impact on the soil. This behavior is observed by the points positioned farther to the right and lower down, representing higher π3 values and lower π4 values. From this

perspective, treatments 2 and 5, composed of the CBC in both AFS arrangements, showed the best results, proving that this machine, in addition to having the lowest soil compaction potential, is capable of covering a management width greater than its own width so as to operate even over the tree rows without the need to travel on the rows.

The good performance of the CBC shown by this graph makes it the most suitable machine for the different AFS arrangements analyzed in this study and reinforces that machines with greater lateral operating capacity and smaller size tend to reduce NMP and traffic on the soil, which, according to Nawaz et al. (2023), are responsible for the degradation of the physical properties of the soil and for compaction, which, in turn, according to Soracco et al. (2015), reduces soil porosity and impairs plant root development. These findings are consistent with studies such as da Luz et al. (2023), which show that traffic management strategies, such as *controlled traffic farming*, can significantly reduce soil compaction caused by mechanized traffic, maintaining the physical properties of the soil when traffic is restricted to permanent lanes, which promotes greater free space for root development and other soil functions.

By ranking the results obtained from the calculations of the specified π-terms (Albiero 2006), together with their behavior in the dimensionless graphs, it was possible to determine the best treatments, with the machine + AFS combinations that obtained the best results for each π-term being counted and listed in descending order. Thus, the treatments were ranked as follows: 1st: treatment 2 (AFS1 + CBC); 2nd: treatment 5 (AFS2 + CBC); 3rd: treatment 3 (AFS1 + GRM); 4th: treatment 6 (AFS2 + GRM); 5th: treatment 1 (AFS1 + RBC); 6th: treatment 4 (AFS2 + RBC). This ranking makes explicit the combinations in which, according to the π-terms, a machine shows better suitability for an agroforestry arrangement, resulting in more satisfactory performance in terms of productivity, operational efficiency and alignment with the UN SDGs.

The Dimensional Analysis method presented here for comparing the suitability of machines for AFS based on the SDGs proves to be highly precise and concise by demonstrating through the dimensionless graphs that, for two different agroforestry arrangements, the CBC stood out in comparison with the other machines evaluated, while the GRM showed intermediate results and the RBC proved to be the least suitable. This phenomenon becomes even more explicit when the comparison is made on the ranking of the π-terms. This demonstrates that Dimensional Analysis can indicate the potential of machines and agroforestry arrangements in such a way as to guide decision-making by farmers, extension agents and public policymakers.

Although the CBC proved to be the most suitable machine for the two AFS studied in this work, since it appears in the best positions in the graphs when compared with the other machines, which means that it is the most energy-efficient machine, has dimensions that are more adaptable to different systems, is capable of covering a management width greater than its own width and has less potential to damage the soil through compaction, it is important to emphasize, however, that this analysis did not take into account two important aspects, especially for family farming: the physical effort and the operator's working time, that is, the higher energy and time expenditures for someone working alone with the CBC in a family farming context. These aspects, as well as financial costs, are complementary to the analyses carried out in this work and were not the focus of this study.

In this sense, it is important to take into account that the RBC presents the lowest values for the variable "operating time" (T) when compared with the other machines, that is, it covers the area to be worked more

quickly and probably with less physical effort from the operator; the opposite is observed for the CBC, that is, it is a machine that takes longer to perform the work and possibly requires greater physical effort. However, the dimensionless graphs, which analyze the phenomenon by taking into account environmental issues and the guidance of the SDGs – in particular π1, which takes "T" into account – clearly demonstrate that the CBC is more suitable for use in AFS because it has other index values that, according to the π-term calculations, demonstrate the superior suitability of smaller machines for these systems, such as lower HGE and TE values also contained in π1 (which is desirable).

In this context, the results showing that the CBC and the GRM present better overall performance corroborate the idea of Yan et al. (2024) that it is not only the presence of mechanization that matters, but also its suitability to the physical and operational context of the system, a principle that emphasizes the importance of choosing appropriate technology to increase the sustainability of production.

4. CONCLUSION

Dimensional Analysis proves to be an effective method for studying the phenomenon of mechanization in AFS, as it was able to clearly demonstrate the potential of the machines in a complete context, thereby allowing the evaluation and comparison of the suitability of machines in different AFS arrangements, which justifies its importance in guiding decision-making by farmers, extension agents and public policymakers.

The dimensionless numbers presented here are fully capable of encompassing a whole range of variables related to different machines, as well as to the arrangements and productivities of different AFS, in such a way as to directly express the best suitability of a machine to a specific AFS, so that this phenomenon is as closely aligned as possible with the UN SDGs.

The study proves that smaller, lower-size machines are more suitable for use in the AFS considered. This can be demonstrated by the better results observed according to the calculations of the dimensional analysis.

Of the three machines evaluated, the CBC proved to be the most suitable, according to the SDGs, for the AFS arrangements studied, which means that it is the most energy-efficient, has more adaptable dimensions, is capable of covering an operating width greater than its own width and has less compaction potential; however, it is important to emphasize that this analysis did not take into account labor-related parameters such as the higher energy and time expenditures of the operator working alone with the CBC in a family farming context, as well as financial costs.

In future applications of this methodology in practical experiments, it is recommended to incorporate replication data and include trend lines in the dimensionless graphs. This makes it possible to communicate the variability of the results, which strengthens the interpretation of the relationships between the π-terms and expands the potential of the analysis to guide decisions on mechanization in AFS.

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