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(Research Article)

Structuring wood-energy exploitation systems and differentiating forest resources in rural Malagasy

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Abstract

In developing countries, wood-energy is the primary source of domestic energy, particularly in Madagascar where it accounts for 80 to 90% of household consumption. However, exploitation practices remain heterogeneous, reflecting a still insufficiently characterized differentiation of systems. The central issue of this study lies in the structuring and differentiation of wood-energy exploitation systems in rural areas, in the face of energy and environmental challenges. The objective is to identify and characterize wood-energy exploitation profiles in rural areas. Two research questions are posed: what are the different types of exploitation activities according to the techniques used, the tree species harvested, and the target market? and, how does exploitation differ according to the types of forest resources harvested? Two hypotheses are proposed: wood-energy exploitation involves different types of activities depending on the techniques used, the tree species harvested, and the target market; and wood-energy exploitation differs according to the types of forest resources harvested. The methodology is based on a survey of 300 operators (farmers, loggers, and charcoal makers) using a mixed-methods approach, combining Multiple Correspondence Analysis and Discriminant Factor Analysis, supplemented by strategic tools such as benchmarking, ranking, and the strategic rectangle. The results highlight the existence of two distinct classes of operators. Comparative analysis allows these classes to be interpreted as two systems: a traditional system representing 52.3% and a modernized system representing 47.7%. These results demonstrate a structuring of the systems around technical, economic, and institutional factors and underscore the role of plantations in the transition to more sustainable systems.

Keywords: Energy plantations; Regeneration; System typology; Forest exploitation; Sustainable management

1. Introduction

At the international level, biomass, and in particular wood-energy, remains an essential source of energy for populations in developing countries. In many regions of Africa, Asia and Latin America, it represents a dominant share of domestic energy consumption, particularly in rural areas, due to limited access to modern energy sources and low household income levels [1, 2].

In Madagascar, this energy dependence is particularly pronounced. Wood-energy, including firewood and charcoal, is the primary energy source for more than 80 to 90% of households, both in rural and urban areas [4, 5, 6]. This strong dependence, combined with population growth, rapid urbanization, and insufficient energy alternatives, puts considerable pressure on forest resources, contributing to deforestation and ecosystem degradation [7].

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At the regional level, particularly in the Arivonimamo district (19° 01′ 47″ south, 47° 15′ 42″ east), this pressure is exacerbated by the proximity of large urban centers such as Antananarivo, a major consumer of wood-energy. This situation fosters the development of various forms of timber exploitation, ranging from traditional practices in natural forests to more organized systems based on plantations, especially eucalyptus.

However, these exploitation methods are not homogeneous. They vary according to the techniques used, the tree species harvested, regeneration practices, compliance with regulations, and market opportunities. This diversity reflects a contrasting reality, characterized by the persistence of unsustainable traditional systems and the emergence of more structured practices oriented towards improved resource management ([8, 9].

Faced with this contradictory reality, the challenge lies in structuring and differentiating wood-energy systems in rural areas, in light of energy and environmental issues. The objective is to identify and characterize the profiles of wood-energy exploitation in rural areas.

Two research questions are posed:

- What are the different types of exploitation activities according to the techniques used, the species harvested, and the clientele?
- How does exploitation differ depending on the types of forest resources exploited?

Two hypotheses are put forward:

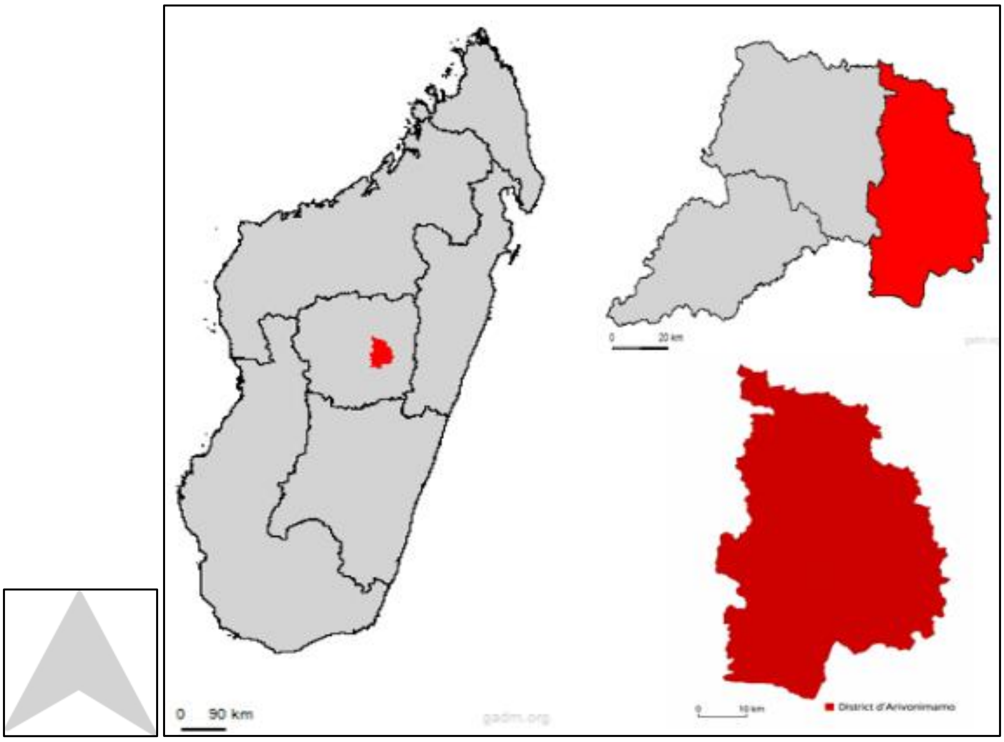
- The exploitation of wood-energy presents different types of activities depending on the techniques used, the species exploited and the clientele;
- The exploitation of wood-energy differs according to the types of forest resources exploited.

2. Methods

2.1. Study area

The study was conducted in the district of Arivonimamo, located in the Itasy region, in central Madagascar. This district is located in the central Malagasy Highlands, characterized by a relief of volcanic plateaus, hills and exploited valleys (19° 01′ 47″ south, 47° 15′ 42″ east) at an average altitude of between 1,200 and 1,500 meters and an area of 1,627 km2 (Figure 1).

This area is characterized by a strong dependence on wood-energy, due to its proximity to major urban centers such as Antananarivo, a significant consumer hub. The district exhibits a diversity of forest management systems, ranging from traditional practices based on natural forests to more organized systems relying on plantations, particularly eucalyptus. This diversity makes it a relevant area for analyzing the differentiation of wood-energy management systems.



Source: IJPSAT 2022

Figure 1 Geographical location of the Arivonimamo district in the Itasy region

2.2. Data collection

The population studied consists of actors involved in the wood-energy sector, including farmers, forestry operators (loggers) and charcoal producers. These actors are involved at different levels of the production, processing and marketing chain.

The study is based on a sample of 300 operators, selected using a reasoned approach to represent the diversity of practices and operating profiles in the study area (Table 1). Since the size of the target population is unknown, the sample size was determined using Cochran's [15] formula, which is used to estimate the minimum sample size when the variable under study is expressed as a proportion.

$$n = \frac{t^2 * p(1-p)}{e^2}$$

With a 95% confidence level (t = 1.96), an estimated proportion p = 0.5, and a margin of error e = 5%, leading to a theoretical sample size of approximately 384 individuals. However, due to the lack of precise information on the proportion of the phenomenon being studied, the value p = 0.5 is generally retained to maximize the sample size. However, considering a more realistic estimate ($p \approx 0.25$), the theoretical sample size is approximately 288 individuals, which remains consistent with the final sample of 300 respondents.

The collected data were entered, coded and processed according to its nature.

Table 1 Composition of the survey sample.

Category of actors	Identification codes	Effective	Percentage %
Farmers using wood-energy	A1 – A86	86	29
Lumberjacks / cutters	B1 – B108	108	36
Producers / charcoal makers	P1 – P106	106	35
Total		300	100

2.3. Data processing

Data analysis relies on two complementary categories of tools: statistical tools and strategic tools.

2.3.1. Statistical tools

Multiple Correspondence Analysis (MCA) was used to explore the relationships between qualitative variables and identify the main dimensions of the structure of forest management systems. It allows us to visualize the proximities between categories and to identify homogeneous profiles.

Discriminant Factor Analysis (DFA) was then used to validate the groups identified by MCA and to determine the most discriminating variables, i.e. those which contribute most to the differentiation of profiles.

2.3.2. Strategic tools

Benchmarking

Following the Discriminant Factor Analysis (DFA), the characterization of each group was further developed through a benchmarking analysis, inspired by the work of Camp (1989). This approach made it possible to examine the relationship between the identified groups and the variables describing wood-energy exploitation practices, particularly the technical, economic, and organizational variables. It thus highlights the specific characteristics of each group with respect to the variables by comparing them to the maximum values corresponding to the benchmarks.

Scheduling

An analysis of the correlation matrix was performed to assess the relationships between the variables and to identify the structural factors of the system. The significance threshold $|\rho|$of the correlation coefficients was established using Student's t-test applied to Pearson's correlation coefficient [16], according to the following relationship:

$$|\rho| = \frac{t_{\alpha=0,05}}{\sqrt{n-2+t_{\alpha=0,05}^{2}}}$$

Or

t :	Student's t-test (1.96)
n :	Number of operators surveyed (300)
$\lvert\rho\rvert$:	Significance of correlation (0.113)

Next, the elements above the diagonal whose absolute values exceeded the significance threshold were used and replaced with "x". Variables with a minimum value at the correlation's significance threshold were not considered significant.
Correlation analysis made it possible to obtain the ordering, by counting the number of "x" per line, then gradually grouping the variables relating to the minimum number in order to identify the main variables affecting the structuring of the wood-energy system.

Strategic Rectangle

Dominance and influence effects were assessed to identify influential and dominant variables. Inter-variable correlations were used to verify the significance and influence of the variables. Non-significant variables $|\rho|$(<0.113) were eliminated, and then the X and Y values were calculated. The X values were sorted in descending order, and those greater than 1 were grouped as influential variables. The Y values were also sorted in descending order, and the highest values were grouped as the most dominant variables.

$$X = {}^{L}/_{P} \ et \ Y = L \times P$$

Or

L: Sum of the absolute values of the row variables in the correlation matrix
P: Sum of the absolute values of the variables in the column of the correlation matrix

2.4. Thematic data analysis

Under hypothesis 1, a multiple correspondence analysis (MCA) was performed, followed by Discriminant Factor Analysis (DFA), to identify and validate the operating profiles. This approach was complemented by a comparative benchmarking analysis to characterize the resulting groups (Table 2).

Table 2 Variables

Variable codes	Variables	Modality code	Modalities
SA	Activity status	J	Daily worker status
SE	Area	1	Exploited area < 1 hectare
		2	Exploited area ≥ 1 hectare
E	Experience	1	1 to 5 years of experience
EE	Species exploited	E	Eucalyptus species
		M	Mimosa essence
TC	Technical	M	Modern technique
RR	Forest resource regeneration	A	Absence of regeneration
		N	Natural regeneration
CP	Potential customers	C	Household clientele
		M	Commercial clientele
PM	Average price per bag	3	Average price of a bag of charcoal ≈ 25,000 Ariary
		4	Average price of a bag of charcoal ≈ 30,000 Ariary
RG	Regulation	N	Lack of regulation
DK3	Land disputes	N	Absence of land disputes
DK4	Production cost	N	Absence of Production Cost
DK5	Low profitability	N	Absence of difficulty related to low profitability
DK6	Funding difficulties	N	No funding difficulties
DK7	Low yield	N	Absence of Low Yield
DK8	Lack of innovation	N	Lack of innovation
DK9	Species extinction	N	Absence of Species Extinction
DK10	Drought	N	Absence of Drought
DK11	Rainfall	N	Absence of difficulty related to rainfall
DK12	Pollution	N	Absence of Pollution
DK13	Permit problems	N	No License Problems
DK14	Informal trade	N	Absence of Informal Trade
DK18	Supply difficulties	N	Absence of permit-related difficulties

As part of hypothesis 2, a ranking of the variables was carried out from the correlation matrix, followed by the construction of a strategic rectangle, allowing the identification of the influential and dominant variables in the structuring of the system (table 3).

Table 3 Variables

Variable codes	Variables	Code of Procedures	Terms and conditions
SE	Area	2	Exploited area ≥ 1 hectare
		1	Exploited area < 1 hectare
E	Experience	1	1 to 5 years of experience
EE	Extracted essence	E	Eucalyptus species
		M	mimosa essence
RR	Forest resource regeneration	HAS	Lack of regeneration
CP	Potential customers	C	Household clientele
PM	Average price per bag	3	Average price of a bag of charcoal ≈ 25,000 Ariary
RG	Regulation	N	Lack of regulation
DK5	Low profitability	N	Lack of Low Profitability
DK6	Funding difficulties	N	No funding difficulties

3. Results

3.1. Structuring of wood-energy exploitation systems

3.1.1. Classes obtained

The MCA reveals a structuring of wood-energy exploitation practices into two distinct classes: class 1 and class 2 (figure 2).

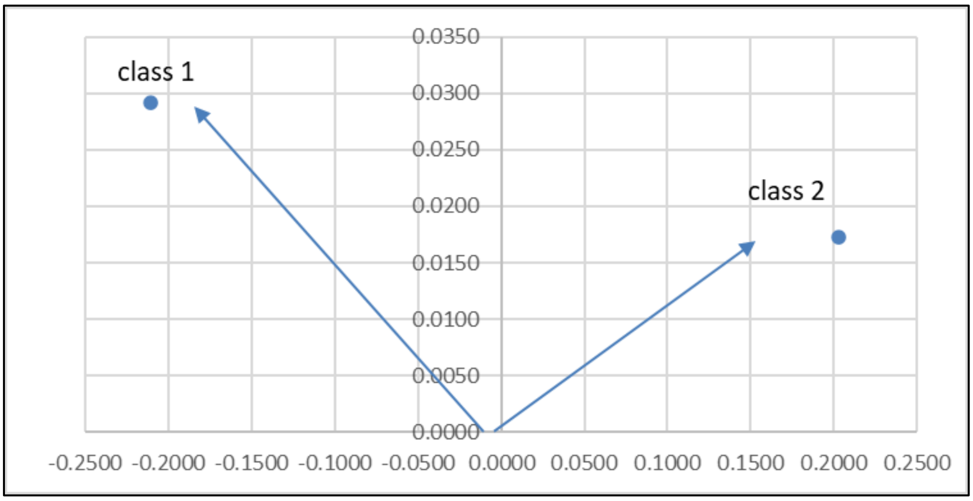


Figure 2 Representation of the two typological classes

Class 1 (52.3%) is characterized by a lack of regeneration (RR-A), exploitation of natural resources, and a focus on local customers, particularly households (CP-C). Conversely, class 2 (47.7%) is based on the exploitation of plantations, particularly eucalyptus (EE-E), combined with natural regeneration practices (RR-N) and a focus on commercial markets (Table 4).

Table 4 Typological group

Class	Frequency	Percentage (%)
class 1	157	52.3
class 2	143	47.7
Total	300	100

This distribution shows the existence of two exploitation profiles within the studied population, corresponding to distinct configurations of practices.

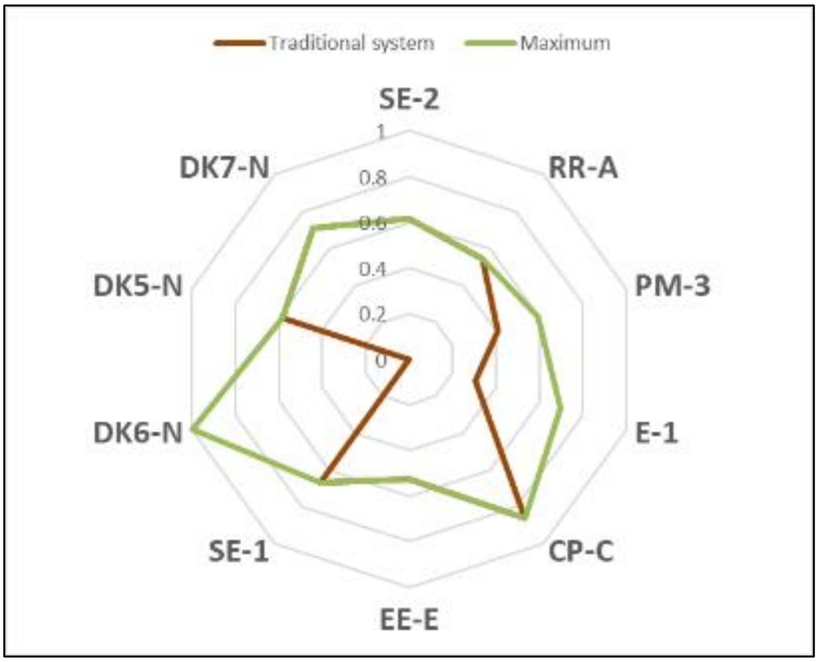
3.1.2. Benchmarking

Benchmarking highlights differences between the two classes resulting from MCA, based on the technical, economic and organizational variables represented in the radial diagrams (figures 3 and 4).

Figure 3, corresponding to class 1, shows a strong representation of household customers (CP-C), the absence of regeneration (RR-A), and the size of exploited areas, both for areas greater than or equal to 1 hectare (SE-2) and for areas less than 1 hectare (SE-1). The absence of difficulties related to low profitability (DK5-N) and the absence of difficulties related to low yield (DK7-N) are also well represented in this profile. Conversely, the average price of a bag of charcoal at 25,000 Ariary (PM-3) and the absence of difficulties related to financing (DK6-N) appear to be poorly represented. Eucalyptus cultivation (EE-E) occupies a less prominent position in this profile.

Figure 4, corresponding to class 2, shows a strong representation of the average price of a bag of charcoal at 25,000 Ariary (PM-3), 1 to 5 years of experience (E-1), and the absence of financing difficulties (DK6-N). Eucalyptus cultivation (EE-E) is more prevalent than in class 1. The absence of regeneration (RR-A) appears less pronounced than in class 1. Household clients (CP-C) and plots smaller than 1 hectare (SE-1) are underrepresented.

Thus, Class 1 presents a profile dominated by household clients, the absence of regeneration, and the areas under cultivation. It corresponds to the traditional system. Class 2 presents a profile marked by the average price of charcoal, the absence of financing difficulties, the experience of the stakeholders, and a greater presence of eucalyptus. It corresponds to the modernized system.



Legends :

SE-2 : Area exploited ≥1 hectare

RR-A : No regeneration

PM-3 : Average price of 25,000 Ar

E-1 : 1 to 5 years of experience

CP-C : Potential household customer

EE-E : Species exploited: eucalyptus

SE-1 : Area exploited < 1 hectare

DK6-N: No financing difficulties

DK5-N: No difficulties related to low profitability

Figure 3 Class 1: Traditional system

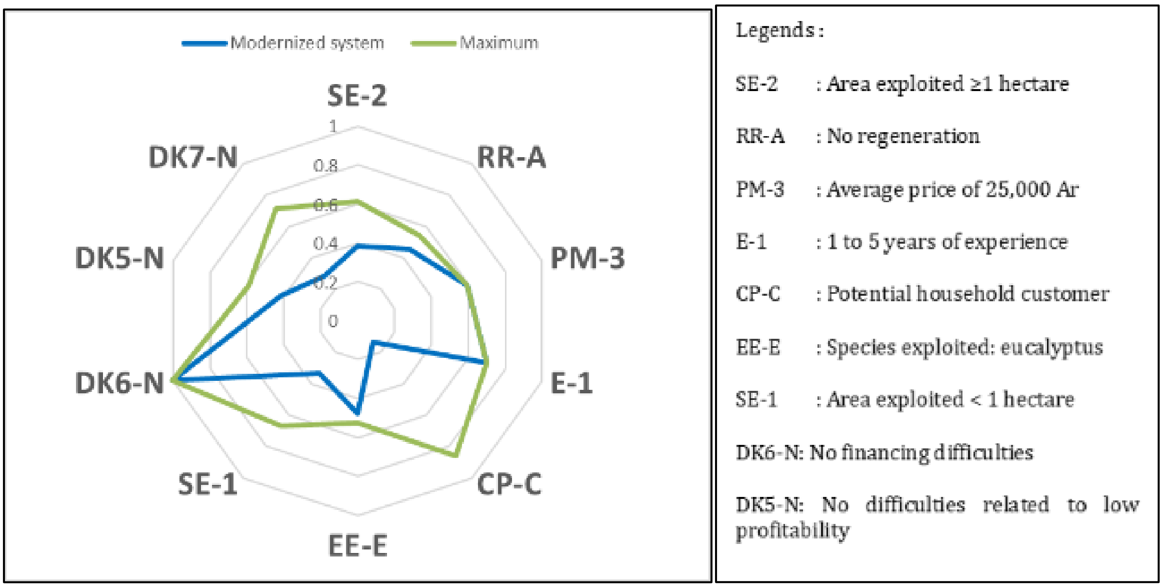


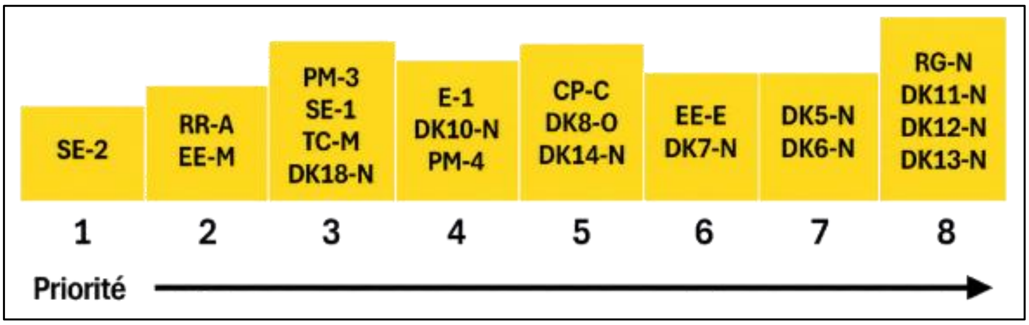
Figure 4 Class 2: Modernized system

3.2. Differentiation of the types of forest resources exploited

3.2.1. Variable ordering

Correlation analysis identified significant relationships between variables in the wood-energy system. Correlations were selected based on a significance threshold set at | ρ | ≥ 0.11.

The ordering of variables was established based on the number of significant correlations observed in the matrix. Variables were ranked according to their level of connection with other categories. The exploited area greater than or equal to 1 hectare (SE-2) occupies the first position. It is followed, at the second level, by the absence of regeneration (RR-A) and the exploitation of mimosa (EE-M). The third level includes the average price of a bag of charcoal (PM-3), the exploited area less than 1 hectare (SE-1), modern techniques (TC-M), and the absence of supply difficulties (DK18-N). The other variables occupy intermediate or lower levels, reflecting their complementary role in structuring the system (Figure 5).



Legends

SE-2 : exploited area ≥ 1 hectare;
RR-A : absence of regeneration of forest resources;
EE-M : species exploited: mimosa;
PM-3 : average price of a bag of charcoal estimated at 25,000 Ariary;
SE-1 : area under cultivation < 1 hectare;
TC-M : modern technique;
DK18-N: no supply difficulties;
E-1 : 1 to 5 years of experience;
DK10-N: absence of drought;
PM-4 : average price of a bag of charcoal estimated at 30,000 Ariary;

CP-C : clientele consisting mainly of households;
DK8-0: presence of difficulties related to lack of innovation;
DK14-N: no difficulty related to informal trade;
EE-E : species exploited: eucalyptus;
DK7-N : absence of difficulty related to low yield;
DK5-N : absence of difficulty related to low profitability;
DK6-N : absence of difficulties related to financing;
RG-N : absence of regulation;
DK11-N: no difficulties related to precipitation;
DK12-N: no pollution-related difficulties;
DK13-N: no difficulties related to permits.

Figure 5 Ordering of variables according to their level of correlation

3.2.2. Dominant and influential variables

The variables resulting from the ranking constitute the dominant and influential variables. The values obtained place the exploited area greater than or equal to 1 hectare (SE-2) in first place according to the overall dominance indicator, followed by the absence of regeneration (RR-A) and the average price of a bag of charcoal of 25,000 Ariary (PM-3). The variables E-1, CP-C, and EE-E occupy an intermediate position, while DK6-N, DK5-N, and RG-N have lower values in the ranking (Table 5).

Table 5 Dominant and influential variables from the correlation matrix.

Variables		$X = L/P$	$Y = L \times P$
Influential and dominant	SE-2	1.26	2.82
	RR-A	1.94	2.45
	PM-3	1.16	1.92
	E-1	1.75	1.75
	CP-C	1.55	1.55
Influential	EE-E	1.37	1.37
	DK6-N	1.17	1.17
	DK5-N	1.11	1.11
	RG-N	1.00	1.00

4. Discussion

4.1. Diversity of exploitation conditions and duality of wood-energy systems

The results show that wood-energy exploitation systems in the Arivonimamo district are not homogeneous. This differentiation stems from the diversity of access to forest resources, regeneration practices, techniques used, and market opportunities. Indeed, operators do not have the same resources, do not use the same tree species, and do not operate according to the same economic principles. Those who rely primarily on natural resources remain more closely associated with a traditional system, while those who manage plantations, particularly eucalyptus, are moving towards a more structured and market-oriented system. This situation explains the formation of two distinct categories in the MCA results.

4.2. MCA structuring between traditional system and modernized system

The results of the MCA show two profiles of wood-energy exploitation: a traditional system representing 52.3% of respondents and a modernized system representing 47.7% (Figure 2; Table 4). This distribution reflects a clear differentiation of exploitation systems within the studied population. Class 1 includes the majority of operators and corresponds to the traditional system, while class 2 comprises a slightly smaller proportion of operators and corresponds to the modernized system. This statistical structure confirms that wood-energy exploitation practices are not homogeneous, which aligns with the analyses of Bailis et *al.* [2] in tropical countries, according to which the impacts and organizational forms of wood-energy vary according to exploitation methods, biomass renewal conditions, and territorial contexts.

4.3. Benchmarking gaps between technical modernization and structural constraints

Benchmarking clarifies this differentiation between the two profiles (Figures 3 and 4). Figure 3, corresponding to class 1, shows a strong association with household clientele (CP-C), the absence of regeneration (RR-A), and the areas exploited (SE-2 and SE-1). This configuration explains its connection to the traditional system, as it reflects exploitation geared towards domestic needs, with high pressure on resources and little consideration for forest renewal. This result aligns with Zulu and Richardson [14], in sub-Saharan Africa, who show that charcoal constitutes a source of energy, income, and sustenance for rural households, while often remaining linked to the livelihoods of local populations. The low level of PM-3 indicates less price stability around 25,000 Ariary, while the low representation of DK6-N shows that the absence of financing difficulties is not characteristic of this class. Financing may therefore remain a significant constraint for this profile. This situation is consistent with the observations of Arnold et *al.* [1] in developing countries, which found that rural wood-energy systems are strongly influenced by local economic conditions, livelihoods, and limited access to productive resources. However, the DK5-N and DK7-N variables show that low profitability and low yield are not the most frequently reported constraints in this class.

Conversely, Figure 4, corresponding to class 2, shows a strong association with the average price of charcoal at 25,000 Ariary (PM-3), 1 to 5 years of experience (E-1), and the absence of financing difficulties (DK6-N). The low representation of household customers (CP-C) indicates that this class is less dependent on direct domestic consumption and may be more open to other outlets, particularly urban or commercial ones. Eucalyptus exploitation (EE-E) is also more prevalent than in class 1. This configuration explains its connection to the modernized system, as it reflects greater economic stability, less pronounced financing constraints, and a more favorable orientation towards market organization. In Madagascar, Minten et *al.* [12] show that the charcoal trade is strongly structured by the relationships between rural producing areas and urban consuming markets. This also aligns with Schure et *al.* [13], in the Democratic Republic of Congo, who analyze the commercial production of wood-energy destined for urban centers, particularly the supply of Kinshasa. In the case of Arivonimamo, the proximity of Antananarivo may therefore reinforce the market orientation of the modernized system.

The sequencing and strategic rectangle indicate that SE-2, RR-A, and PM-3 occupy a central place in the system's structure (Figure 5, Table 5). This is because these variables respectively relate to access to the resource, ecological renewal, and economic incentives. The area exploited determines production capacity, the absence of regeneration reflects a risk of resource depletion, while the price of charcoal influences production and marketing decisions. These results are consistent with those of Hosonuma et *al.* [10], who, in developing countries, show that deforestation and forest degradation result from a combination of economic, institutional, and environmental factors.

Comparing the benchmarking figures shows that the traditional system is more closely linked to a domestic logic, a marked lack of regeneration, and a potential financing constraint

(Figure 3). The modernized system is distinguished by greater price stability, less dependence on households, a more pronounced absence of financing difficulties, and a more significant presence of eucalyptus (Figure 4). These results are consistent with Blaser et *al.* [9], in tropical forests, emphasize that sustainable management depends on institutional frameworks and the organization of practices. They also agree with Lamb [11], at the international level, that plantations can contribute to productive intensification, but only if they are integrated into coherent ecological management.

4.4. Role of regeneration and regulation in system differentiation

The role of regeneration and regulation also appears crucial (Figure 5; Table 5). This importance stems from the fact that sustainability depends not only on the availability of wood, but also on the capacity to organize exploitation, renew the resource, and control practices. The FAO [8], at the global level, rightly emphasizes that wood-energy systems must be supported by management, planning, and control mechanisms to limit pressure on forest resources. Thus, even when a system appears more organized or more market-oriented, its sustainability remains contingent upon regeneration, harvest control, and institutional oversight.

Thus, the results confirm that the differentiation of wood-energy exploitation systems depends on the interaction between forest resources, regeneration practices, the market, techniques, and institutional frameworks. This interpretation confirms the study's two hypotheses: the systems exhibit differentiated profiles, and this differentiation depends on the types of resources harvested, particularly between natural resources and plantations.

5. Conclusion

This study aims to identify and characterize wood-energy exploitation systems in rural areas, as well as the factors explaining their differentiation. The results obtained show the existence of two distinct profiles: a traditional system, marked by a strong focus on household customers, a lack of regeneration, a large proportion of harvested land, and a potential constraint related to financing; and a modernized system, characterized by greater stability in charcoal prices, a greater absence of financing difficulties, a more prominent presence of eucalyptus, and less dependence on household customers.

These results confirm the hypothesis that wood-energy exploitation systems exhibit differentiated profiles depending on operator practices, market opportunities, economic conditions, and resource management methods. They also validate the hypothesis that this differentiation depends on the types of forest resources harvested, particularly between natural resources and plantations.

From a scientific perspective, this study contributes to a better understanding of the mechanisms structuring wood-energy systems, highlighting the crucial role of technical, economic, ecological, and institutional factors. From a practical perspective, it underscores the importance of strengthening regeneration programs, improving support for stakeholders, stabilizing the economic conditions of the sector, and promoting energy plantations to foster sustainable forest resource management.

Finally, further research could incorporate socio-economic and environmental indicators to deepen the analysis of the sustainability of systems, to measure their effects on forest resources and to assess their evolution over time.

Compliance with ethical standards

Acknowledgments

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Disclosure of conflict of interest

The authors state that there is no competing interest associated with this manuscript.

Statement of ethical approval

This study was carried out in accordance with the ethical requirements applicable to field surveys. The participants were informed of the purpose of the research before data collection, and their participation was based on consent. The data collected were used exclusively for scientific analysis. Respondents' anonymity and confidentiality were maintained, and no information allowing individual identification is disclosed in the manuscript

Statement of informed consent

Informed consent was obtained from all individual participants included in the study.

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