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Planning and stakeholder coordination in the sustainability of the wood-energy cycle: A prospective analysis in Madagascar

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Abstract

In developing countries, wood-energy is a major source of energy for households, particularly in rural areas where access to modern alternatives remains limited. This dependence generates increasing pressure on forest resources and poses a sustainability challenge for the system. The problem lies in the conditions for the sustainability of the wood-energy cycle, characterized by high pressure on resources and weak organization among stakeholders. The objective is to assess the extent to which forest resource planning and stakeholder coordination can stabilize the system and reduce pressure on forest resources. The research focuses on the following questions: how can sustainable forest management planning contribute to stabilizing the wood-energy cycle and sustainably meeting needs? and does stakeholder coordination improve the sustainability of the forest system to reduce pressure on resources? The hypotheses suggest that sustainable forest management planning contributes to stabilizing the wood-energy cycle and sustainably meeting needs, and that coordination among stakeholders improves the system's sustainability and reduces pressure on resources. The methodology is based on an analytical and forward-looking approach, combining system modeling over a ten-year horizon with organizational analysis using the Programme Evaluation and Review Technique (PERT). The results show that planning improves resource regeneration, reduces structural constraints, and stabilizes economic variables. The PERT analysis highlights a critical path structured around production, processing, marketing, and consumption, which determines the system's functioning. These results demonstrate that sustainability relies on the complementarity of planning and coordination, and open up avenues for strengthening institutional frameworks and improving the organization of wood-energy sectors.

Keywords: Forest Resources; Prospective Analysis; PERT Diagram; Stakeholder Coordination; Sustainability; Rural Systems.

1. Introduction

Forest biomass is currently one of the world's main sources of energy, particularly in developing countries where it represents a significant share of domestic energy consumption. According to the FAO [1], the International Energy Agency [2], and the United Nations Environment Programme [3], nearly 2.4 billion people still rely on wood-energy to meet their daily energy needs, raising major challenges related to sustainability and natural resource management. Furthermore, the [4] emphasizes that unsustainable forest exploitation contributes significantly to greenhouse gas emissions.

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Several studies show that biomass-based energy systems rely on complex dynamics involving technical, economic, and institutional factors [5, 6]. The sustainability of these systems depends in particular on the ability to reconcile resource exploitation and forest regeneration, as well as the effectiveness of governance mechanisms [7].

Across Africa, dependence on wood-energy is particularly high, especially in rural areas where access to modern energy remains limited. Wood-energy accounts for more than 70% of energy consumption in many sub-Saharan African countries [2, 5, 6]. This situation is exacerbated by population growth and rapid urbanization, which increase pressure on forest resources [8].

In Madagascar, this energy dependence is even more pronounced. Annual wood consumption is estimated at between 80 and 100 million cubic meters, while deforestation reaches approximately 200,000 hectares per year. Wood-energy is the primary energy source for the majority of households, which increases pressure on forest resources and compromises their regeneration capacity [1, 10].

This situation reveals a contradictory reality. On the one hand, wood-energy represents an essential resource for rural populations due to its accessibility. On the other hand, its harvesting, often unplanned and poorly regulated, contributes to the progressive degradation of forest resources. Furthermore, harvesting systems are not homogeneous and vary according to technical practices, tree species harvested, and the level of organization of stakeholders [7, 12].

In this context, the sustainability of the wood-energy cycle emerges as a major challenge, particularly in an environment characterized by high pressure on resources and weak stakeholder organization. The central question of this study lies in the conditions for the sustainability of the wood-energy cycle within this context of high pressure on resources and weak stakeholder organization.

The objective is to assess the extent to which forest resource planning and stakeholder coordination can stabilize the system and reduce pressure on forest resources.

Two research questions are posed:

- How can sustainable forest management planning contribute to stabilizing the wood-energy cycle and sustainably meeting needs?
- Does coordination between actors improve the sustainability of the forest system to reduce pressure on resources?

Two hypotheses are put forward:

- Sustainable forest management planning helps to stabilize the wood-energy cycle and sustainably meet needs.
- Coordination between actors improves the sustainability of the system and reduces pressure on resources.

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 cultivated 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 km^2

From a socio-economic perspective, the population relies primarily on subsistence farming, small-scale trade, and activities related to forestry. High poverty rates and limited access to electricity reinforce households' dependence on wood biomass to meet their domestic energy needs. This energy pressure occurs within a context of progressive degradation of forest resources, characterized by a decrease in forest cover and an increase in unregulated logging practices.

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 [11] 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%, this leads to a theoretical sample size of approximately 384 individuals. However, in the absence of precise information on the proportion of the phenomenon being studied, the value p = 0.5 is generally used to maximize the sample size. Considering a more realistic estimate ($p \approx 0.25$), the theoretical sample size is approximately 288 individuals, which remains consistent with the selected 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 code	Number of individuals	Proportion (%)
Farmers using wood-energy	A1 – A86	86	28.7
Lumberjacks / cutters	B1 – B108	108	36.0
Producers / charcoal makers	P1 – P106	106	35.3
Total		300	100.0

2.3. Data processing

2.3.1. Statistical tools

Preliminary statistical analyses, notably Multiple Correspondence Analysis (MCA) and Discriminant Factor Analysis (DFA), were used to identify the operating profiles and discriminating variables of the wood-energy system. Multiple Correspondence Analysis, developed within the French school of data analysis based on the work of Benzécri [14], allowed for the exploration of relationships between qualitative variables, the identification of similarities between categories, and the distinction of homogeneous actor profiles. DFA was then used to validate the groups resulting from MCA and to determine the variables that contribute most to the differentiation of profiles.

In this article, the MCA and the DFA are not the main results. They are considered as a methodological basis that allowed us to select the modernized and traditional configurations, as well as the variables used in the prospective and organizational analysis.

The data collected made it possible to characterize the technical, economic and organizational variables of the system, serving as the basis for the analysis of the overall functioning of the wood-energy cycle (Table 2).

Table 2 Grouping of variables

Dimension	Code	Variable
Technical	SE-2	Exploited area ≥ 1 ha
	SE-1	Exploited area < 1 ha
	RR-A	Lack of regeneration
	EE-E	Exploited species
Economic	PM-3	Average price of a bag of charcoal: 25,000 Ariary
	CP-C	Households as potential customers
	DK4-N	Absence of difficulty related to the cost of production

Dimension	Code	Variable
	DK5-N	Absence of difficulty related to low profitability
Organizational	E-1	Years of experience: 1 to 5 years
	SA-J	Daily worker status
	RG-N	Regulations not enforced
	DK3-N	Absence of difficulty related to land disputes
	DK6-N	Absence of difficulty related to financing
	DK7-N	Absence of difficulty related to low yield
	DK9-N	Absence of difficulty related to the disappearance of species

2.3.2. Strategic tools

Prospective analysis

The prospective analysis was conducted through a qualitative projection over a ten-year horizon. It consists of examining the evolution of the selected variables according to three trends: increase, decrease, or irregular evolution, considering two system configurations: a modernized system and a traditional system. This approach makes it possible to identify the system's potential trajectories based on the interactions between the variables.

Organizational analysis

The organizational analysis was conducted using a PERT diagram. This diagram was constructed by identifying the main stages of the wood-energy cycle: production, processing, marketing, and consumption, as well as the relationships between these activities. It is not a direct extension of the statistical analyses, but rather draws upon their results to structure the overall functioning of the system. This approach makes it possible to determine the critical path of the system and to analyze the role of stakeholder coordination and institutional regulation in the continuity of the cycle.

2.4. Thematic analysis

The thematic analysis is organized around the effect of forest resource planning and the effect of stakeholder coordination, two main axes corresponding to the objectives of the study.

The first focus area concerns the effect of forest resource planning on the stability of the wood-energy cycle. It involves analyzing the evolution of the system's technical and economic variables, including the area harvested, regeneration practices, production, and market indicators, in order to assess their contribution to the system's sustainability.

The second focus area concerns the effect of stakeholder coordination on the functioning of the wood-energy cycle. This analysis is based on the organization of activities, the interactions between stakeholders and the different stages of the cycle (production, processing, marketing and consumption), while integrating the structural constraints highlighted through the PERT diagram.

This structure allows us to interpret the results according to a dual approach: the evolution of the variables of the system and the organization of the interactions between the actors.

3. Results

3.1. Effect of sustainable planning on the stability of the wood-energy cycle

The analysis of the impact of sustainable planning on the wood-energy system is based on a prospective analysis carried out over a ten-year horizon. This approach makes it possible to observe the dynamic evolution of the structuring variables of the system in two distinct configurations: a modernized system, characterized by a more structured organization of activities, and a traditional system, marked by weak planning and strong pressure on natural resources (Figure 1).

3.1.1. Class 2 - Modernized System

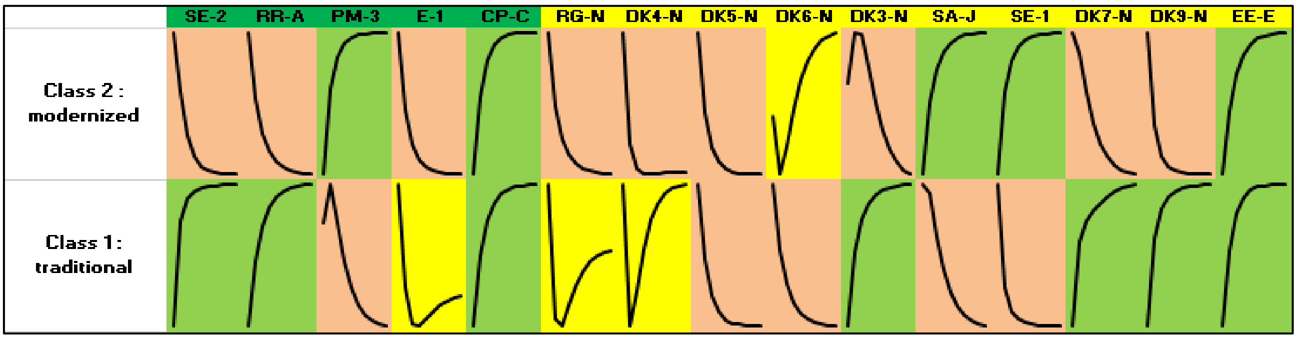
With the modernized system, several variables are evolving favorably, reflecting a progressive improvement in the organization and performance of the system.

The exploited area larger than 1 hectare (SE-2) is decreasing, leading to optimized resource use rather than an expansion of exploited land. Simultaneously, the absence of regeneration (RR-A) is decreasing, indicating improved forest resource renewal practices. Economically, the average price of 25,000 Ariary per bag of charcoal (PM-3) is increasing, reflecting a higher value for the product. The number of household customers (CP-C) is also increasing, confirming a more structured demand pattern. Institutionally, non-compliance with regulations (RG-N) is decreasing, reflecting stronger oversight of activities. Structural constraints related to production costs (DK4-N), low profitability (DK5-N), and low yields (DK7-N) are decreasing, indicating improved production conditions. However, some difficulties, such as financing (DK6-N), initially decrease before increasing again, while land disputes (DK3-N) follow the opposite trend, reflecting adjustments in the system's organization. Furthermore, the number of day laborers (SA-J) increases, which may indicate an intensification of the workforce. Finally, eucalyptus harvesting (EE-E) progresses, confirming the shift towards high-productivity tree species (figure 1).

3.1.2. Class 1 - Traditional System

In the traditional system, the observed dynamics reflect a more unstable and less favorable evolution (figure1).

The area under management exceeding 1 hectare (SE-2) is increasing, reflecting a trend towards expanding acreage to compensate for low productivity. Simultaneously, the lack of regeneration (RR-A) is increasing, intensifying pressure on forest resources. Economically, the average price (PM-3) rises slightly before falling, indicating market instability. Operator experience (E-1) decreases then increases slightly, which may reflect a restructuring of the stakeholders. Non-compliance with regulations (RG-N) initially decreases before increasing, reflecting a lack of institutional stability. Constraints related to production costs (DK4-N) decrease then increase sharply, while yield difficulties (DK7-N) and species disappearance (DK9-N) increase, indicating a progressive deterioration of production conditions. Conversely, the variables related to the absence of difficulty in low profitability (DK5-N) and financing (DK6-N) decrease, but this does not lead to an overall improvement in the system. The daily wage status (SA-J) decreases, while the share of small farms (SE-1) also decreases, reflecting a reduction in small-scale activity. Finally, eucalyptus harvesting (EE-E) also increases in this system, but without significant improvement in the other variables, which limits its impact on overall sustainability (figure 1).



Legends: SE-2 : exploited area greater than 1 hectare ; **DK6- N:** absence of difficulty with financing; **RR-A :** absence of regeneration ; **DK3- N:** land dispute;**PM-3 :** average price of a bag of charcoal at 25,000 ariary ; **SA-J :** daily status; **E-1 :** experience of 1 to 5 years; S **E-1 :** exploited area less than 1 hectare; **CP-C :** potential household customers ; **DK7- N:** absence of difficulties with yield ; **RG-N :** no regulation ; **DK9- N:** species extinction; **DK4- N:** absence of difficulty with production costs ; **EE-E :** eucalyptus species ; **DK5- N:** absence of difficulty with low profitability

Figure 1 Comparative prospective evolution of key variables

3.2. Effect of stakeholder coordination on system sustainability

The corrected PERT diagram allows us to represent the interactions between the different stages of the cycle and to identify the critical activities that condition its operation (figure 2).

The critical path is structured around the sequence of production (N1), processing (N2), marketing (N3), and consumption (N4) activities. This chain constitutes the functional framework of the wood-energy system, insofar as these activities are interdependent and must be carried out sequentially to ensure the continuity of the cycle.

Indeed, production (N1) determines the availability of wood resources. Any shortage at this stage leads to a supply disruption affecting the entire system. Processing (N2), particularly carbonization, is a key step in adding value to wood, enabling its conversion into a usable energy product. Marketing (N3) ensures the distribution of the product to markets, while consumption (N4) represents the culmination of the energy cycle.

Thus, any disruption at one of these critical stages directly impacts the entire system, reflecting their crucial role in the stability of the wood-energy cycle. This sequential dependence highlights the importance of effective coordination between the stakeholders involved at each level.

Furthermore, institutional regulation (N5) appears as a cross-cutting factor influencing all stages of the process. Although it is not part of the main critical path, it plays a central role in structuring the system by ensuring the framework for activities, the application of standards, and the organization of actors. Its intervention helps to improve the synchronization of the different stages and to limit system dysfunctions.

The analysis also highlights the existence of feedback loops between consumption (N4) and production (N1), reflecting a dynamic of system adjustment based on demand. An increase in consumption leads to an intensification of production, which can increase pressure on resources in the absence of regulatory mechanisms.

In a context of weak coordination, these interactions are poorly structured, leading to disruptions in the flow of resources, increased delays, and overall system inefficiency. Conversely, enhanced coordination optimizes interactions between stakeholders, streamlines production and distribution flows, and improves forest resource management.

The use of the PERT model thus makes it possible to identify the critical points of the system and to propose levers for improvement based on better organization of activities and strengthening of inter-actor coordination.

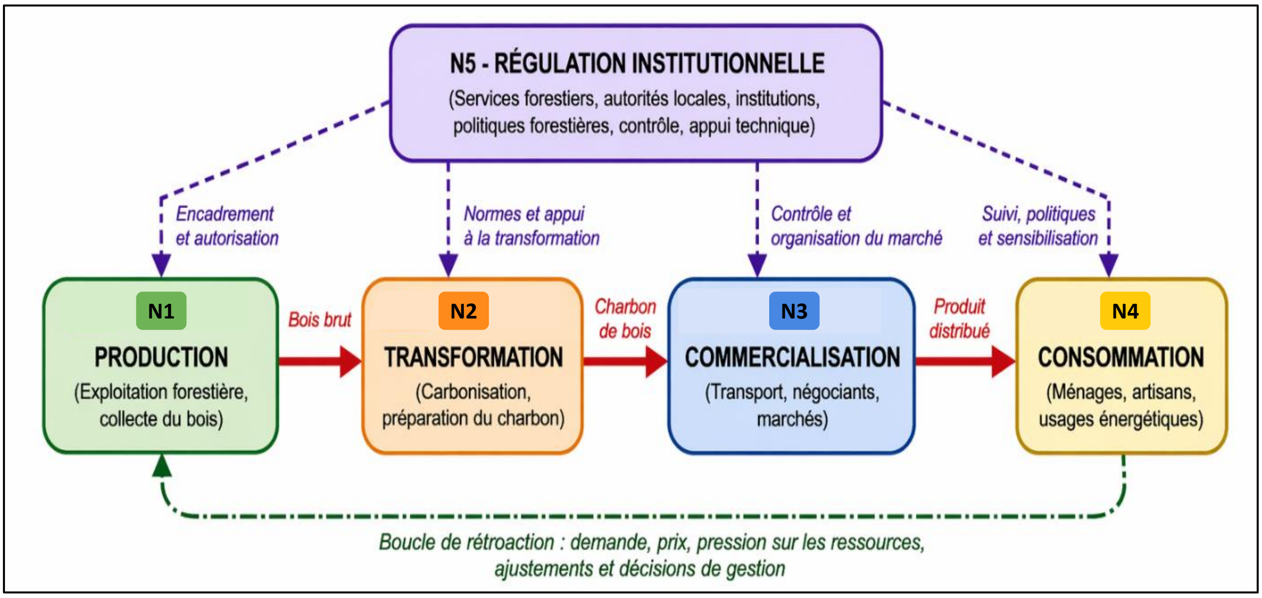


Figure 2 PERT diagram of the wood-energy system

4. Discussions

4.1. Forest planning, improved regeneration, and economic stabilization as levers for controlling the wood-energy system

The results concerning the effect of forest resource planning (Figure 1) show contrasting trajectories between the modernized and traditional systems. In the modernized system, improved regeneration (decreasing RR-A), reduced production constraints (DK4-N, DK5-N, DK7-N), and the stabilization of economic variables (PM-3) reflect a more efficient system organization. This trend is explained by the fact that a planned system allows for better control of harvested areas, better organization of resource renewal, and a reduction in production constraints. Conversely, the traditional system is characterized by an increase in the absence of regeneration, an expansion of harvested areas (SE-2), and a progressive degradation of production conditions, indicating increased pressure on forest resources. This instability is explained by a compensatory logic: when productivity is low and regeneration is insufficient, operators tend to expand harvested areas to maintain production. These results confirm that resource planning is a central lever for stabilizing the wood-energy system, consistent with the work of the FAO [1], globally, which underlines the importance of sustainable management in the renewal of forest resources, and with the IPCC [4], internationally, which shows that unsustainable exploitation of forest resources accentuates the degradation of ecosystems.

From this perspective, planning must prioritize three key elements of the system. First, it concerns the management of exploited areas, through limiting the expansion of these areas and promoting more intensive and controlled harvesting. Second, it involves strengthening regeneration practices, particularly through reforestation or assisted regeneration, to ensure the renewal of forest resources. Third, it must incorporate the regulation of economic variables, especially monitoring prices and production volumes, to avoid market imbalances. These elements are necessary because the sustainability of charcoal production depends on resource availability, renewal, and economic value. These forms of planning align with the analyses of Blaser [12], in the context of tropical forest plantations, and of the FAO [1], at the global level, which emphasize the role of forest management and harvesting control in the sustainability of wood-energy systems.

Furthermore, the analysis highlights that technical, economic, and organizational variables evolve in an interdependent manner. The reduction of unregulated activity (RG-N) and the improvement of regeneration practices are accompanied by a greater economic valuation of charcoal and a progressive structuring of demand (CP-C). This interaction is explained by the fact that producers react simultaneously to regulatory rules, conditions of access to resources, and market economic signals. The sustainability of the system therefore depends not only on resource management but also on economic incentives and the organization of stakeholders. These results are consistent with those of Arnold *et al.* [5] in developing countries and Bailis *et al.* [6] in tropical countries, who demonstrate that wood-energy systems rely on a combination of technical, economic, and institutional factors.

4.2. Coordination of stakeholders, continuity of supply and reduction of disruptions in the stages of the wood-energy cycle

The analysis of actor coordination using the PERT diagram (Figure 2) reveals a critical path structured around the stages of production (N1), processing (N2), marketing (N3), and consumption (N4). This sequential organization demonstrates that the continuity of the cycle depends on the coordination between these activities, with any disruption at one stage leading to a dysfunction of the entire system. This is explained by the direct interdependence between the stages: without sufficient production, processing through carbonization is limited; without processing, marketing cannot ensure supply; and without organized marketing, consumption becomes unstable. These findings highlight the central role of actor coordination in the stability of the system, in line with the work of CIFOR [7] in tropical forest countries, which emphasizes the importance of governance and the organization of forest supply chains.

In concrete terms, coordination must be applied to the interactions between stakeholders at each stage of the cycle. This involves, firstly, organizing the flows between production, processing, and marketing to ensure continuity of supply and minimize disruptions. Secondly, it requires better structuring of relationships between stakeholders, particularly through activity planning, operational synchronization, and reduced product transit times. This coordination is necessary because wood-energy, and more specifically charcoal, involves several categories of stakeholders whose actions are interdependent. Finally, it necessitates strengthening the role of institutions in regulating practices, monitoring standards, and organizing the market, as highlighted by CIFOR [7].

4.3. Institutional regulation, framework standards and feedback mechanisms in the face of increased pressure on resources

Furthermore, the cross-cutting role of institutional regulation (N5) appears crucial in structuring the system. Although it is not part of the critical path, it influences all stages of the cycle by ensuring the framework for activities and the implementation of standards. Its importance stems from the fact that regulation prevents the demand for charcoal from automatically leading to an uncontrolled intensification of harvesting. The existence of feedback loops between consumption and production also reflects a dynamic of system adjustment based on demand, which can increase pressure on resources in the absence of effective regulation. These observations are consistent with those of Hosonuma et *al.* [13] in developing countries, which highlight the role of institutional factors in deforestation and the degradation of forest resources.

4.4. Complementarity between planning and coordination as a condition for the sustainable stabilization of the wood-energy system

The results show that the sustainability of the wood-energy system relies on a complementary relationship between resource planning and stakeholder coordination. Planning influences the evolution of system variables, while coordination ensures the continuity and efficiency of interactions between the different stages of the cycle. This complementarity is necessary because planning without coordination risks remaining theoretical, while coordination without planning may improve short-term flows without guaranteeing resource renewal. This dual dynamic allows for a better understanding of the conditions necessary for system stabilization in a context of high resource pressure. It aligns with the analyses of Arnold *et al*. [5], in developing countries, and Bailis et *al*. [6], in tropical countries, who consider wood-energy systems as complex systems linking forest resources, livelihoods, markets, technical practices, and institutions.

5. Conclusion

This study analyzed the conditions for the sustainability of the wood-energy system, highlighting the role of forest resource planning and stakeholder coordination. The results show that planning stabilizes key system variables, including regeneration, economic conditions, and structural constraints, while stakeholder coordination ensures the continuity of the cycle through improved organization of production, processing, marketing, and consumption flows. These results confirm the two initial hypotheses.

From a scientific perspective, this study makes a contribution by combining a prospective approach with an organizational analysis of the wood-energy system, leading to a better understanding of sustainability dynamics in rural contexts. From a practical perspective, it highlights the need to strengthen planning mechanisms, improve coordination among stakeholders, and consolidate institutional frameworks to promote the sustainable management of forest resources.

Finally, research perspectives can be considered, including the integration of complementary socio-economic and environmental variables, as well as the extension of the analysis to other areas in order to better understand the territorial dynamics of the wood-energy system.

Compliance with ethical standards

Acknowledgments

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Disclosure of conflict of interest

The authors declare that they have no conflict of interest regarding the publication of this article.

Statement of ethical approval

The study was conducted in accordance with ethical principles applicable to field research. The respondents were informed about the purpose of the study before data collection, and their participation was voluntary. The information collected was used only for scientific purposes. The confidentiality and anonymity of the respondents were respected throughout the research process, and no personal identifying information is presented in this article.

Statement of informed consent

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

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