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SUSTAINABLE USE OF NATIVE BAMBOO FROM ACRE, AMAZONIA, BRAZIL: POTENTIAL FOR THE PRODUCTION OF BIOPLASTICS, BIOCHAR AND CHARCOAL

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ABSTRACT
Brazil faces a critical challenge: the growth of rural production combined with the reduction of environmental impacts. The bioeconomy emerges as a promising alternative to this dilemma, especially in the state of Acre, where bamboo forests, which cover 62% of the territory, offer significant economic and environmental opportunities. This study investigates the sustainable exploitation of native bamboo, with a focus on species of the genus Guadua, through a comprehensive forest inventory carried out in seven municipalities of Acre. The methodology included taxonomic analyses, sampling and statistical treatment of the data, revealing a predominance of the species Guadua weberbaueri, which, despite its limitations for the furniture industry, has potential for the production of bioplastics, biochar and charcoal. The results indicate an estimated 21.8 billion culms and 800.1 million m³ of bamboo in Acre, highlighting the relevance of this renewable resource in mitigating climate change, promoting biodiversity, and replacing conventional plastics. The research concludes that, to ensure sustainable bamboo exploitation, it is essential to implement public policies, strengthen production chains and involve local communities. Thus, bamboo can become a symbol of a sustainable economic future integrated with environmental conservation in the Amazon.

Keywords: Native bamboo. Guadua weberbaueri. Bioeconomy. Sustainability. Amazon.

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INTRODUCTION

Brazil faces a crucial challenge: to promote the growth of rural production while reducing the environmental impacts associated with this activity. This dilemma is widely discussed in national and international forums, in which a development model is sought that reconciles economic growth with environmental conservation, ensuring the well-being of present and future generations (IPEA, 2012).

The economic literature indicates that the intensive exploitation of natural resources often results in the generation of negative externalities, which are not adequately reflected in market prices. Such externalities result, among other factors, from the difficulty of clearly defining property rights and the high transaction costs involved (MOTTA, 2011). This means that impacts such as environmental degradation, loss of biodiversity, compromise of ecosystem services, and damage to the health of local communities end up being socialized, falling on the community and not only on exploitative agents. As a result, the absence of efficient mechanisms to internalize such costs tends to favor unsustainable practices, aggravating social, economic, and environmental imbalances. Thus, it is essential to strengthen environmental public policies, capable of guiding the responsible use of natural resources, promoting the restoration of degraded ecosystems, encouraging clean technologies, and establishing regulatory frameworks that ensure greater efficiency in the allocation and management of resources.

In this scenario, the strategic potential of native bamboo as a viable economic and ecological alternative stands out, particularly in the state of Acre. Bamboo forests, which cover about 62% of the state's territory, represent one of the largest continuous extensions of this type of vegetation in the entire South American continent. This natural heritage, although still underutilized, offers significant opportunities for sustainable development. Among the predominant species, those of the genus Guadua stand out not only for their wide geographical distribution, but also for their physical and environmental properties. They contribute directly to soil conservation, regulation of the hydrological cycle, and carbon sequestration, in addition to offering potential for various productive applications (FERREIRA et al., 2020; SILVA, 2019).

The ecological characteristics of bamboo, especially the species Guadua *weberbaueri*, have been widely discussed in studies that address the sustainable use of forest resources and the conservation of Amazonian biodiversity (COSTA; PEREIRA, 2021). The use of bamboo as a renewable resource has gained prominence for its ability to regenerate quickly, its adaptability to different soils and its economic viability. In the State of Acre, bamboo occupies the understory of open forests in approximately 4,563,688 hectares, which represents about 28% of the state territory, resulting in an estimated 800.1 million m³ of available volume.

Although Guadua *weberbaueri* is not ideal for the furniture industry, its use is promising in the production of bioplastics, biochar and charcoal, sectors with high demand and growth potential. The rational and planned exploitation of this resource requires, however, investments in research, technical training, processing infrastructure and mechanisms to encourage sustainable production. The active participation of local communities, the strengthening of production chains, and the creation of specific public policies for the sector are essential for bamboo to become a vector of sustainable development and conservation of the Amazon rainforest.

METHODOLOGY

DATA SOURCE AND PLACE OF RESEARCH

The research was conducted based on taxonomic studies and a forest inventory contracted by the Acre State Technology Foundation - Funtac, which provided data on the occurrence of bamboo species, their morphometric characteristics and distribution in different municipalities of Acre. The analysis included the estimation of the commercial and total volume of the species, as well as the amount of stalks per hectare, allowing a detailed understanding of the exploitation potential. The study areas are in the municipalities of Feijó, Manoel Urbano, Sena Madureira, Bujari, Rio Branco, Porto Acre and Xapuri, totaling 144,000 hectares (Figure 1).

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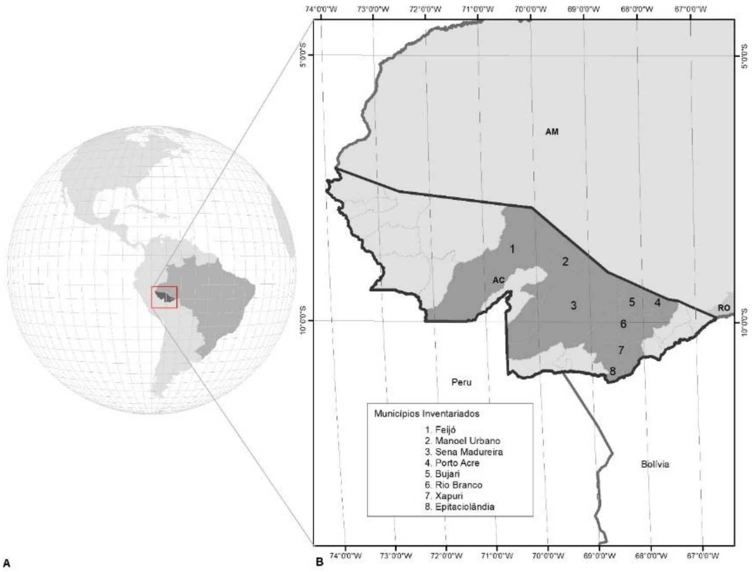
Figure 1 – Distribution of municipalities in which a forest inventory of bamboo occurrence was carried out in the state of Acre.

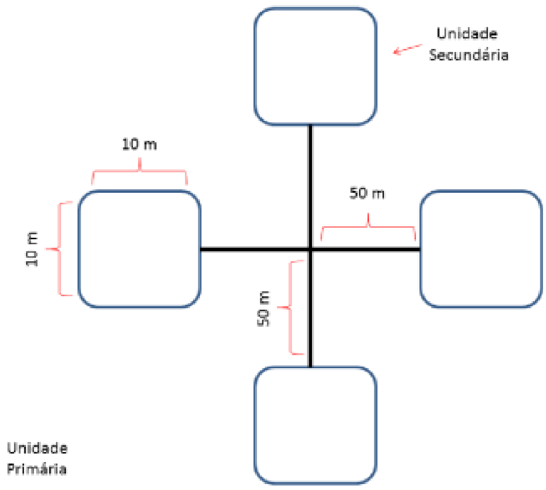


Source: Illustrative image of the location of the municipalities where the data collection took place.

SAMPLING USED

The definition of the sampling system took into account the size and conditions of access to the inventoried areas, the characteristics of the inventoried population and the experience of similar surveys in the region. The sample areas are equivalent to 9 primary units with 4 secondary units for each of the 7 municipalities in the state of Acre, in which the inventories were carried out, totaling 67 clusters. These samples were collected in 10m x 10m plots installed in each cluster, totaling an area of 400 m2 per cluster (Figure 2).

Figure 2 - Shape of the sample units.



Source: Survey Data.

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TABULATION AND PROCESSING OF DATA

The field data were digitized and systematized using the MS Excel software. The statistical treatment was performed using the data analysis software SAS – *Analytics & Solutions Software*.

RESULTS

SPECIES DISTRIBUTION AND DENDROMETRIC PARAMETERS OF NATIVE BAMBOO

According to data from the State Program for Ecological-Economic Zoning of the State of Acre. Ecological-economic zoning of Acre - Phase II: Synthesis document (Acre, 2010), in Acre there are 8 classifications of forests distributed throughout its municipalities, all of them with occurrence of bamboo.

Corroborating the above description, Carmo et. Al, 2017, "observed that the occurrence of bamboo in Acre is concentrated in eight forest typologies, which appear in greater proportion in the central region of the state, occupying about 28% of the Acre territory. By considering bamboo not as a forest component, but as part of the biomass of the forest typology, it is possible to achieve an increase of more than 10% in those typologies in which there is a dominance of bamboo in the understory. More than 40% of the total area deforested in Acre in the last 10 years consists of bamboo forests." However, in the inventoried sample, 6 of the typologies described in Acre (2010) were identified, a fact that contributes as an indication that the inventoried plots were effectively chosen in places of massifs in a biased way, a fact that contributes to the validation and extrapolation phase of the sample. Table 1 shows the distribution of bamboo by forest typology in the inventoried municipalities.

Table 1 - Composition of the typologies of the inventoried sample.

Typology	Municipality in the state of Acre, Brazil						
	BJ	FJ	MULE	PA	RBR	SM	XP
Open Forest with Bamboo + Open Forest with Palms - FAB+FAP	56%	15%	67%	22%	11%	22%	44%
Open Forest with Palm Trees + Open Forest with Bamboo - FAP+FAB	22%	-	33%	11%	56%	22%	22%
Open Forest with Palms + Open Forest with Bamboo + Dense Forest - FAP+FAB+FD	-	15%	-	-	22%	22%	-
Open Forest with Dominant Bamboo - FABD	-	46%	-	-	11%	33%	33%

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Open Alluvial Forest with Bamboo - FAB-Aluvial	-	8%	-	67%	-	-	-
Open Forest with Bamboo + Dense Forest - FAB+FD	22%	15%	-	-	-	-	-

Source: Primary data.
Where: BJ – Bujari-AC, FJ – Feijó-AC, MU – Manoel Urbano-AC, PA – Porto Acre-AC, RBR – Rio Branco-AC, SM – Sena Madureira-AC and, XP – Xapuri-AC.

In the table above, it can be seen the predominance of bamboo in 6 of the 7 typologies in the municipality of Feijó-AC, followed by Rio Branco-AC and Sena Madureira, which were the municipalities where the presence of bamboo was confirmed in 4 of the 7 forest typologies occurring in the state of Acre.

GROWTH CHARACTERISTICS

The data showed that the species Guadua *weberbaueri* is the most common, with a predominance of 87% in the sample. However, species such as Guadua *angustifolia* (5%) and Guadua *sarcocarpa* (8%). Table 2 presents the main dendrometric characteristics of the sample.

Table 2 - Occurrence, height, area and measured volume of bamboo species in the sample.

Species	Prevalence (%)	Estimated height (m)			Basal Area (m²)	Commercial Volume (m³)	Total Volume (m³)
		Minimum	Medium	Maximum			
Guadua *angustifolia*	5%	5,00	12,73	23,00	0,44	0,52	8,70
Guadua *sarcocarpa*	8%	1,20	13,76	27,00	0,39	1,24	5,88
Guadua *weberbaueri*	87%	1,30	13,77	23,00	5,82	12,14	90,20

Source: Primary data.

In the same way, it is possible to observe the behavior of the occurrence of diameter classes, indicating a higher concentration in the class that varies between 50 and 60 centimeters, indicating that the sample presents a concentration of mature individuals suitable for commercial exploitation (Figure 3).

Figure 3 – Distribution of diametric classes in the sample.

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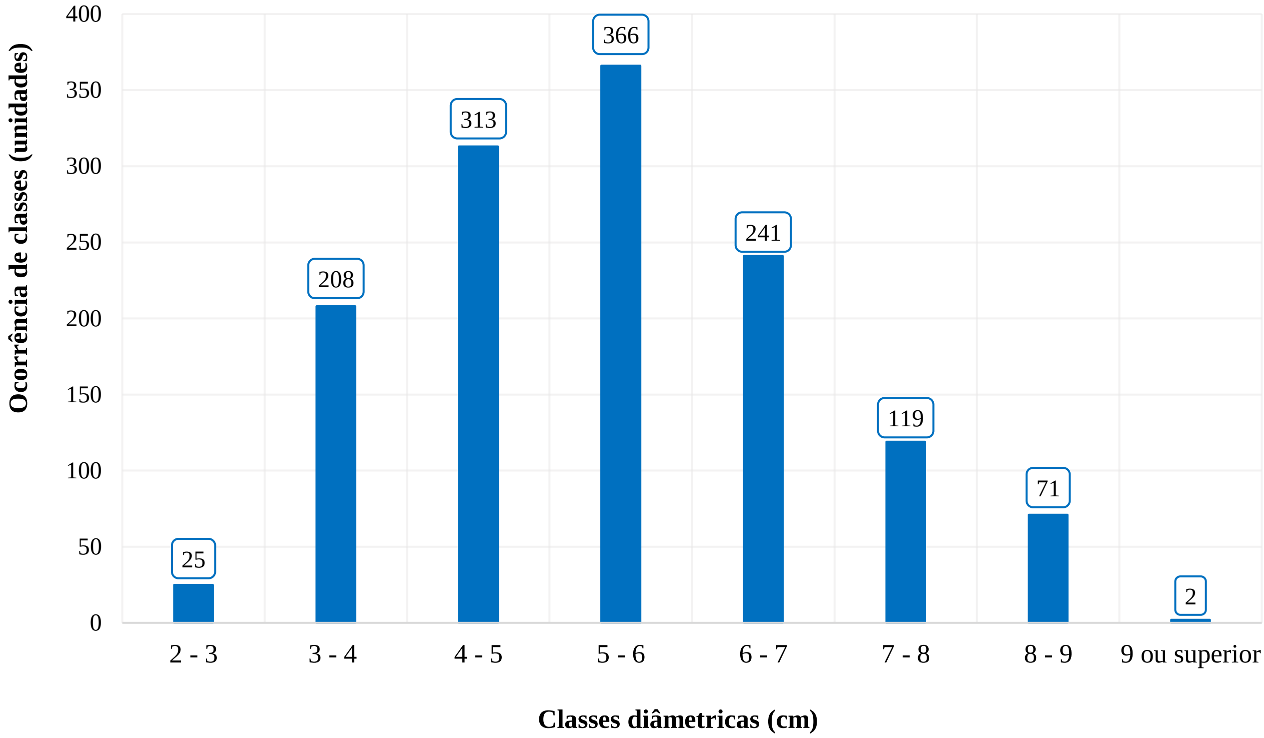

Source: Primary data.

The highest predominance of stalks by diameter classes is concentrated between classes 3-4 and 6-7, which is characterized as being a sample in the development phase, composed mostly of young stalks, and also by the predominance of Guadua *weberbaueri*, dominant in the sample.

To calculate the total estimates, the number of stalks and the volume of bamboo for the state of Acre, Brazil, the average indices of the confidence interval of each plot (100 m²) were multiplied by the area equivalent to one hectare and then by the total area of the typologies.

Based on this modeling, and considering an interval of 95%, the results point to a total estimate of approximately 21.8 billion stalks and 800.1 million m³ of bamboo occurrence in the State of Acre, and such volumes are distributed by forest typologies and species of the genus Guadua (Table 3).

Table 3 – Total estimates of the number of stalks and volumetry (in m³) by typology and species of Guadua spp. in the State of Acre.

	G. *angustifolia*	**G. *Sarcarp***	**G. *Weberbaueri***

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Guadua Spp. / Forest Typology	No. of thatches (One thousand units)	Volume (thousand m³)	No. of thatches (One thousand units)	Volume (thousand m³)	No. of thatches (One thousand units)	Volume (thousand m³)
FAB - Alluvial	-	-	-	-	201.375	5.191
FAP - Alluvial	-	-	468.050	11.233	1.018.477	25.275
FAB + FAP	-	-	1.719.150	28.382	5.716.986	129.747
FAB + FAP + FD	-	-	-	-	779.220	50.949
FABD	-	-	987.300	31.265	2.492.933	106.958
FAP + FAB	-	-	677.370	13.547	3.386.850	158.053
FAP + FAB + FD	2.138.479	155.369	2.229.111	84.158	-	-

Source: Survey data.

In summary, according to Almeida (2017), "the bamboo stalk lamination process comprises a set of concatenated operations, such as collection and geometric-quantitative control of the stalk, production of slats, immunization and assembly of pieces with a predominantly rectangular or quadrangular section. The culms are appropriate for the production of the lath in terms of wall thickness and must meet the following specifications: piece length over 120cm, diameter over 140mm, wall thickness over 15mm and internode distance of at least 300mm. The parts must not present deformations or cracks".

Based on the data presented, the species Guadua weberbaueri, which represents 87% of the sample, does not fully meet the minimum standards necessary for the production of glued laminated bamboo, as described by Almeida (2017). Although this species demonstrates a total volume of 90.20 m³ per hectare, its physical characteristics, such as wall thickness and stem length, are not specified in the information provided, which makes it difficult to confirm its suitability for the rolling process. In addition, the predominance of Guadua *angustifolia* and Guadua *sarcocarpa*, with 5% and 8%, respectively, is also not enough to meet the demand for stalks that meet the quality criteria required for the production of glued laminated bamboo (BLaC).

On the other hand, the versatility of Guadua *weberbaueri* can be exploited in alternative applications, such as the production of composites, bioplastics, biochar and charcoal. These products do not require the same strict criteria as lamination, allowing the characteristics of Guadua *weberbaueri* to be leveraged widely and effectively. The use of this raw material for these purposes can represent a significant opportunity for sustainable development and for the valorization of bamboo in the region, contributing to the diversification of products and the increase in the added value of the species.

POTENTIAL FOR THE PRODUCTION OF BIOPLASTICS, BIOCHAR AND CHARCOAL

Bioplastics

Bamboo, due to its composition rich in cellulose and lignin, is an excellent raw material for the production of bioplastics. Bamboo-derived bioplastics are biodegradable and can replace conventional plastics, reducing environmental impact. Furthermore, the replacement of fossil materials by bamboo in the production of bioplastics presents a series of environmental gains and advantages from the perspective of sustainability.

Bamboo is a renewable resource, with rapid growth and the ability to regenerate after harvest, making it an attractive alternative to materials derived from fossil fuels. From the perspective of the environmental gains resulting from this adoption, the following stand out:

1. Reduced Greenhouse Gas Emissions: Growing bamboo can contribute to reducing CO2 emissions. As a fast-growing plant, bamboo efficiently sequesters carbon during its life cycle. According to research by Wang et al. (2019), bamboo can store a significant amount of carbon, helping to mitigate climate change, quickly and in single crops or intercropped with forest species;
2. Efficient Use of Water Resources: Bamboo requires less water compared to other crops such as traditional wood. As highlighted by Liu et al. (2018), the efficiency of bamboo water use makes it a viable option in regions where water scarcity is a growing concern;
3. Biodiversity and Ecosystems: Bamboo cultivation can promote biodiversity by serving as a habitat for various species. The practice of sustainable bamboo cultivation helps in soil conservation and erosion reduction, according to Zhang et al. (2020); and
4. Replacing Conventional Plastics: Bamboo-derived bioplastics contribute to reducing dependence on conventional plastics, which are petroleum-based and have a significant environmental impact. According to Khan et al. (2021), bioplastics are biodegradable and therefore offer a solution to the problem of plastic waste.

And yet, in relation to the advantages from a sustainable perspective, the following can be listed:

1. Renewability: Bamboo is a highly renewable plant, with harvest cycles that can occur every 3 to 5 years, while traditional trees can take decades to grow. This

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characteristic makes the production of bamboo bioplastics a more sustainable practice compared to oil extraction;

2. Mechanical and Functional Properties: Bioplastics made from bamboo may have superior mechanical properties compared to conventional plastics. According to González et al. (2020), bamboo biocomposites have good strength, flexibility, and can be used in various applications, from packaging to consumer products; and
3. Local Economic Development: The bamboo industry can provide employment opportunities and economic development in rural communities by promoting sustainable farming practices. Zhou et al. (2021) highlight that the cultivation and production of bamboo products can improve the quality of life in rural areas.

In this context, the replacement of fossil materials with bamboo in the production of objects derived from bioplastics represents a promising strategy to promote environmental gains and sustainability. With its ability to sequester carbon, resource efficiency, and potential to reduce plastic pollution, bamboo stands out as a viable and eco-friendly alternative. As an intergovernmental development organization promoting environmentally sustainable development using bamboo and wicker, INBAR – *The International Bamboo and Rattan Organization* and China have jointly launched the Bamboo as a Plastic Substitute (BASP) initiative. The BASP initiative aims to provide bamboo-based solutions to plastic pollution, using bamboo efficiently as a sustainable substitute for energy-intensive and hard-to-deteriorate plastic products in nature, as well as to mitigate climate change by proactively contributing to achieving the global action plan for bamboo as a plastic substitute, target 2023-2030, Yanxia et al. (2023).

Biochar

Regarding biochar, produced from bamboo, it can be used as a soil improver, increasing organic matter contents, water retention and nutrient absorption in the soil, improving structure, and contributing to the mitigation of climate change. Furthermore, according to Bringas, et al. (2020), "With the application of biochar at doses of 80 and 160 grams, trends of increase in height, stem thickness, aerial and root biomass of the indicator crop were observed. However, these results were inferior to those obtained with the fertilized treatment. The results obtained would be associated with the improvement of the substrate characteristics after application of the organic additive in the form of biochar. In this sense, the application of *Guadua angustifolia* Kunth biochar in the soil is a sustainable strategy for the use of forest plantation residues, due to its potential contribution to the improvement of soil structural conditions and as a generating agent of favorable conditions for the assimilation of nutrients by plants".

Charcoal

Bamboo charcoal has gained prominence as a sustainable and efficient alternative in various applications, from water purification to use as fuel. Bamboo, a fast-growing and renewable plant, when charred, results in a material with adsorbent properties and high porosity, making it effective in removing pollutants and toxins.

One of the main advantages of bamboo charcoal is its ability to adsorb volatile organic compounds (VOCs) and other contaminants. Studies show that bamboo charcoal can be used in water purification, acting in the removal of heavy metals and pathogens (Wu et al., 2015). In addition, due to its porous structure, it is ideal for applications in air and water filters, contributing to the improvement of environmental quality. In the energy context, bamboo charcoal also has a high calorific value, making it a viable option for biofuels. Burning bamboo charcoal emits fewer pollutants compared to fossil fuels, contributing to the reduction of greenhouse gas emissions (Zhou et al., 2018). Thus, bamboo charcoal presents itself as a promising solution for sustainable development, aligning the use of renewable resources with the mitigation of environmental impacts.

ALIGNMENT OF RESEARCH RESULTS WITH THE SUSTAINABLE DEVELOPMENT GOALS (SDG/UN 2030)

This research, according to the theme, results and recommendations, aligns with the following SDGs:

- SDG 1 - Poverty Eradication: By exploring the economic potential of bamboo, the study can contribute to income generation and employment opportunities in local communities, helping to eradicate poverty.
- SDG 8 - Decent Work and Economic Growth: The research promotes the creation of sustainable production chains around bamboo, which can lead to economic growth and the generation of decent jobs in the regions where bamboo is grown and exploited.
- SDG 12 - Responsible Consumption and Production: The focus on the production of bioplastics and biochar from native bamboo aligns with the need to

reduce the use of conventional plastics and promote more sustainable production practices.

- SDG 13 – Action Against Global Climate Change: The use of bamboo for biochar and charcoal can contribute to climate change mitigation, given that bamboo is a fast-growing plant that can sequester carbon.
- SDG 15 - Life on Land: The research emphasizes the importance of bamboo in promoting biodiversity and conserving forests, which is essential for the maintenance of terrestrial ecosystems.
- SDG 17 - Partnerships and Means of Implementation: The conclusion of the article on the need for public policies and the involvement of local communities indicates the importance of partnerships and collaborations between different sectors to ensure the sustainable exploitation of bamboo.

These SDGs highlight the importance of an integrated approach that considers both economic development and environmental preservation, reflecting the goals of the UN 2030 Agenda. The research on bamboo in Acre exemplifies how local resources can be used sustainably to meet these global goals.

DISCUSSION

Research on the sustainable use of native bamboo in Acre reveals significant potential for the production of bioplastics, biochar and charcoal. Bamboo species, especially those of the genus Guadua, not only offer a viable alternative to the exploitation of traditional forest resources, but also stand out for their ecological and economic properties. The analysis of the data showed a predominance of Guadua *weberbaueri*, which, although not suitable for the furniture industry, presents promising characteristics for other applications, such as the production of bioplastics and biochar.

Bamboo cultivation can contribute substantially to climate change mitigation, since the plant is efficient in sequestering carbon. This aspect, combined with the efficient use of water resources and the promotion of biodiversity, reinforces the need for investments in sustainable bamboo harvesting practices. In addition, the production of bioplastics from bamboo not only meets the demand for biodegradable materials, but also represents a solution to the growing plastic waste crisis.

The possibility of replacing conventional plastics with bamboo-derived bioplastics is an opportunity that should be explored, especially in a global scenario that seeks more sustainable alternatives.

However, the extraction and use of bamboo must be carried out in a planned and monitored manner. Strategies that balance economic exploitation with environmental conservation are key to ensuring that economic benefits do not result in environmental degradation. The implementation of public policies and incentives for sustainable management practices will be crucial for the success of this endeavor. There needs to be a commitment from local communities, stakeholders and governments if bamboo's potential is to be fully realized.

CONCLUSION

The study carried out on the native bamboo of Acre confirms the viability and potential of this plant as a renewable resource, capable of promoting sustainable and inclusive economic development. Guadua species demonstrate characteristics that not only favor the production of bioplastics, biochar, and charcoal, but also contribute to the mitigation of environmental problems, such as plastic pollution and climate change.

The adoption of bamboo as a raw material for new products must be accompanied by an integrated approach that prioritizes environmental conservation and the strengthening of local communities. The creation of sustainable production chains, combined with investments in research and technology, is essential to ensure success in bamboo exploration.

Initiatives around the sustainable use of bamboo in Acre not only represent an economic opportunity, but also a model to be followed in other regions that seek solutions for the responsible exploitation of their natural resources. The path forward must be tread cautiously and responsibly, ensuring that development aligns with the needs of nature and future generations. Therefore, bioeconomy research, combined with effective public policies, can transform bamboo into a symbol of a sustainable future, where the economy and environmental conservation coexist in harmony.

Finally, this study confirms the viability and potential of bamboo as a renewable resource, capable of promoting sustainable and inclusive economic development. The adoption of bamboo as a raw material for new products must be accompanied by an integrated approach that prioritizes environmental conservation and the strengthening of

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local communities. It is concluded that the initiatives around the sustainable use of bamboo in Acre represent an economic opportunity and a model to be followed in other regions that seek solutions for the responsible exploitation of their natural resources.

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