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Harnessing agro-industrial waste for cellulose extraction and biodegradable packaging production: a study from the Peruvian Amazon

Aprovechamiento de residuos agroindustriales para la extracción de celulosa y la producción de envases biodegradables: un estudio desde la Amazonía peruana

Grober Panduro Pisco [1,3], *Lady Di Hoyos Shica* [1,4], *Edwar Edinson Rubina* [1,5], *Glendy Sánchez Sunción* [1,6], *Gustavo Nilo Panduro Rocha* [1,7], *David Leon Moreno* [1,8], *Dalia Carbonel* [2,9]

[1]Universidad Nacional de Ucayali. Pucallpa, Perú. [2]Universidad Nacional de Ingeniería. Lima, Perú. [3] grober_panduro@unu.edu.pe; [4] hoyos.shica@hotmail.com; [5] erubina@senace.gob.pe; [6] glendy_sanchez@unu.edu.pe; [7] gustavo_panduro@unu.edu.pe; [8] david_leon@unu.edu.pe; [9] dcarbonelr@uni.pe

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Abstract

This study, based in the department of Ucayali in Peru, focuses on quantifying waste from the agro-industry sector and estimating potential cellulose yield for biodegradable packaging production. Given the significant environmental impact of non-degradable plastic packaging, cellulose extracted from waste material offers a sustainable alternative with promising applications in packaging. A sample of 17 agro-industrial enterprises was surveyed to gather data on their production and waste generation. The findings suggest significant potential for cellulose extraction from waste generated in the processing of seven primary crops. Despite positive initiatives to reuse waste, there are opportunities for improvement, particularly regarding the disposal of non-reusable waste. The research provides practical solutions for waste management, highlighting the need for policy measures that encourage its responsible disposal and the reuse of agro-industrial waste. It also stresses the importance of capacity building and training for small and medium-sized enterprises in the sector. The findings present contributions to waste management, environmental conservation, sustainable material production, and policy-making, with implications for both regional and global efforts to foster sustainable practices.

Keywords: Agriculture, bioplastics, Peru, waste management, waste reuse.

Resumen

Este estudio, realizado en el departamento de Ucayali en Perú, se centra en cuantificar los residuos del sector agroindustrial y estimar el rendimiento potencial de celulosa para la producción de envases biodegradables. Dado el importante impacto ambiental de los envases de plástico no degradables, la celulosa extraída de residuos ofrece una alternativa sostenible con aplicaciones prometedoras en este sector. Se encuestó una muestra de 17 empresas agroindustriales para recopilar datos sobre su producción y generación de residuos. Los hallazgos sugieren un potencial significativo para la extracción de celulosa a partir de residuos generados en el procesamiento de siete cultivos primarios. A pesar de las iniciativas positivas para reutilizar los residuos, hay oportunidades de mejora, particularmente en lo que respecta a la eliminación de residuos no reutilizables. La investigación proporciona soluciones prácticas para la gestión de residuos, destacando la necesidad de políticas que fomenten su eliminación responsable y la reutilización de residuos agroindustriales. También destaca la importancia de desarrollar capacidades y formar a las pequeñas y medianas empresas del sector. Los hallazgos presentan contribuciones a la gestión de residuos, la conservación del medio ambiente, la producción de materiales sostenibles y la formulación de políticas, con implicaciones para los esfuerzos regionales y globales para fomentar prácticas sostenibles.

Palabras clave: Agricultura, bioplásticos, gestión de residuos, Perú, reutilización de residuos.

Introduction

Solid waste generation poses a significant global challenge, particularly impacting developing countries and areas like the cities in the Amazon rainforest, where socio-economic and environmental challenges lead to inadequate waste management. In the department of Ucayali in the Peruvian Amazon, despite contributing minimally to Peru's total production and exports, there's significant growth potential in the agro-industry. However, the region faces critical issues related to solid waste management. The lack of proper waste disposal facilities, like sanitary landfills, has resulted in widespread open dumping, posing health hazards and environmental damage (Panduro Pisco, 2021). Recognizing agro-industrial waste as a resource is crucial for environmental protection and business innovation. This waste has a range of applications including organic fertilizer production (Kouser *et al.*, 2024), environmental cleanup (Samraj *et al.*, 2022), and the manufacturing of biodegradable packaging (Ahmad et al., 2024).

In the department of Ucayali alone, the scale of potential agro-industrial waste generation can be directly inferred from the 2020 crop production volumes, as reported by the Integrated System of Agricultural Statistics of the Peruvian Ministry of Agrarian Development and Risk: approximately 862 636 tons of bananas, 886 987 tons of palm oil, and 21 616 tons of cacao (DRA Ucayali, 2020). When compared to national totals, Ucayali's production represents more than 10 % of the country's output in these crops, highlighting the regional importance of these agro-industries. According to the Food and Agriculture Organization (FAO), such agricultural intensities are associated with substantial waste volumes, which, if not managed properly, can lead to severe environmental degradation (FAO, 2023). In Latin America, regions similar to Ucayali report substantial waste across the supply chain for key crops such as cocoa and bananas. For instance, losses during the processing stage can reach up to 20 % for cocoa (*Theobroma cacao*) and nearly 5 % for bananas (*Musa* spp.), often due to inadequate waste management infrastructures that fail to treat or utilize these by-products effectively (FAO, 2022). This context not only frames the gravity of the issue in Ucayali but also echoes a global crisis, emphasizing the urgent need for sustainable waste management strategies.

Accurately quantifying agro-industrial waste is vital to unlock its potential as a cellulose source for sustainable packaging, a strategy applicable in regions with similar socio-economic contexts as the study area and without the need for high-tech solutions. However, currently, there is no comprehensive data available on the volume or composition of waste generated by agro-industrial activities in the region. This absence of data hinders effective waste management strategies and limits the potential for sustainable resource utilization. To address this gap, this research quantifies the agro-industrial waste produced in the department of Ucayali in the Peruvian Amazon, estimates potential waste production, and calculates the yield of cellulosic pulp for biodegradable packaging. By leveraging accessible data from agricultural statistics and company records, the study estimates waste generation rates based on input volume or production levels, such as determining waste output from a rice processing plant based on the final product quantity. Focusing on seven primary crops, the research not only assesses waste generated from crop processing but also explores the innovative use of this waste in cellulose extraction, positioning agro-industrial waste as a valuable resource for sustainable material production. This approach seeks to address global environmental concerns, particularly plastic pollution, and advocates for a shift towards sustainable waste management and business practices. The hypothesis suggests that agro-industrial waste in the region has substantial potential for cellulose extraction, underlining the study's relevance and potential impact on sustainable development efforts, both regionally and globally.

Materials and methods

Location and description of the study area

The study was conducted in the Peruvian provinces of Coronel Portillo and Padre Abad, located in the department of Ucayali (Figure 1). Covering an area of approximately 102 410 km^2 (39 536 sq mi), the region is located in the eastern part of the country and encompasses portions of the Amazon basin. The region's climate is typically hot and humid. The average annual precipitation is approximately 1500 mm in Coronel Portillo and 2000 mm in Padre Abad, with the dry season typically spanning from June to August.

Two distinct ecosystems define the study area: the restinga, a floodable alluvial forest, and the high-altitude area, incorporating both low and high hill forest. The flood seasonality allows for the cultivation of crops with short vegetative periods such as rice, corn, peanuts, beans, cassava, banana, vegetables, and cucurbits. Additionally, crops such as camu camu (*Myrciaria dubia*), sapote (*Pouteria sapota*), and soursop (*Annona muricata*), which can withstand flooding and root saturation during high water levels, are well-suited for these zones. Conversely, the high-altitude areas are located on hills and terraces that are not subject to flooding.

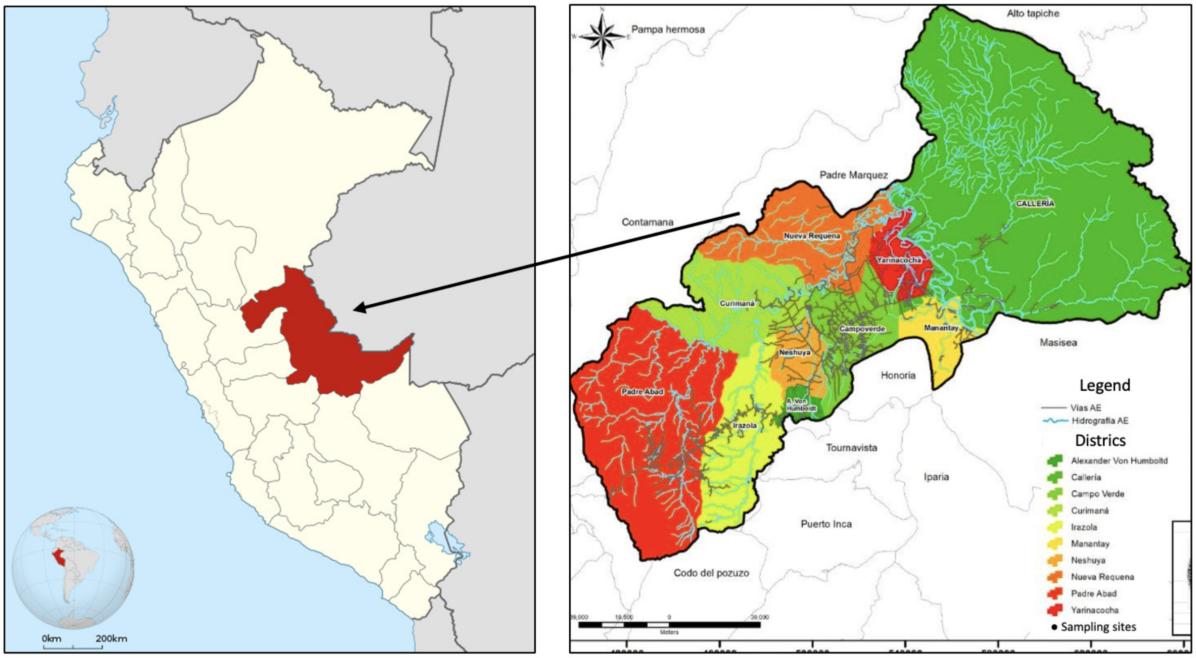

Figure 1. Study area location in Ucayali region, Peru.

Agriculture forms a primary economic pillar in the Ucayali region, conducted predominantly by family units around the department's major rivers and main roads. As per data provided by the Statistics Office of the Regional Office of Agriculture, the region's largest crop production in 2020 was oil palm (*Elaeis guineensis*), banana, cassava (*Manihot esculenta*), and rice (*Oryza sativa*) (Panduro Pisco, 2021).

Population, sample selection and data collection

The study area houses a total of 112 agro-industrial enterprises engaged in processing a variety of inputs, according to data from the Regional Agrarian Directorate of the Department of Ucayali (DRA Ucayali, 2020) (Table S1). 57 agro-industrial enterprises were preliminary selected, employing Equation 1 with a sampling error of 10 %. Initial contact was made with companies that were geographically close to one another, easily accessible, and not located in remote areas far from roads or other companies. Of the 57 companies contacted, 21 were non-operational and 16 did not respond. A total of 20 companies were ultimately surveyed, but only 17 provided comprehensive information about raw material volumes, production, and solid waste generation. With these final numbers, the margin of error was recalculated using Equation 1.

$$n = \frac{Z^2 \cdot p \cdot q \cdot N}{E^2\,(N-1) + Z^2 \cdot p \cdot q} \quad \textbf{(Eq. 1)}$$

Where n represents the sample size, p is the probability of success (set at 87.7 % due to the rural setting and greater dispersion), q is the probability of failure (12.3 %), E is the margin of error, N is the population size (112), and Z is the confidence level (set at 1.96 for a confidence level of 1-a = 95 %). According to the final sample size, the margin of error was redetermined as 14 %.

Surveys were administered in October and November 2020 to companies involved in the processing of sugarcane (*Saccharum officinarum*), rice, cassava, plantain, coffee (*Coffea arabica*), cocoa, and palm oil. During each company visit, a structured survey (Table S2) comprising both closed and open-ended questions was used to gather data on their production, raw material consumption, waste generation, access to basic services, and environmental management practices. Operational managers provided flow charts data (Figure S1).

Data processing

The rates of waste generation per feedstock and product, and feedstock efficiency, were calculated using Equations 2, 3 and 4, respectively.

$$\textit{Waste per feedstock} = \frac{SW}{F} \quad \textbf{(Eq. 2)}$$

$$\textit{Waste per product} = \frac{SW}{P} \quad \textbf{(Eq. 3)}$$

$$\textit{Efficiency}\ (\%) = \frac{F}{P} \quad \textbf{(Eq. 4)}$$

Here, *SW* refers to the monthly volume of solid waste generated (in tons), *F* is the monthly volume of feedstock, and *P* is the monthly production volume (both in tons). Equations 5 and 6 were used to estimate waste and cellulose generation.

$$\text{Waste generation} = \text{Production} \cdot \text{Waste per feedstock} \quad \textbf{(Eq. 5)}$$

$$\text{Cellulose} = \text{Waste generatio} \cdot \%\ \text{cellulose} \quad \textbf{(Eq. 6)}$$

The term "*production*" in these equations refers to the yield of each crop in 2020, as per data from the Integrated System of Agricultural Statistics of the Peruvian Ministry of Agricultural Development and Irrigation (Midagri, 2021). The cellulose percentages were derived from references that specify the chemical composition of each waste type (Table 4).

Results

Environmental management, energy consumption and waste reuse in the surveyed companies

The survey focuses on the agro-industrial activities in a specific area, highlighting the diversity in the scale of operations among enterprises. Larger enterprises, such as those producing alcohol, rice, and palm oil, possess extensive machinery and workforce. In contrast, smaller enterprises, often with less than ten workers, are engaged in producing various products like panela, *aguardiente*, and banana chips. Environmental management is notably lacking in small and medium-sized enterprises, with most perceiving environmental issues as a global rather than local concern. Only one company, Indomalsa, actively employs an environmental management tool. Energy consumption in these companies is primarily derived from non-electric sources, with diesel and wood being common, reflecting a pattern seen in broader agricultural sectors. However, there are disparities in electricity consumption costs among these enterprises, with those in rice production incurring significantly higher costs compared to those in cocoa processing and chocolate production, as detailed in the surveyed data.

Table 1 presents the production characteristics of the surveyed companies, providing detailed insight into the main product, total number of workers, total number of equipment units, frequency of equipment maintenance, and monthly electricity expenditure.

Waste reuse

The flow diagrams in supplementary Figure S1 depict the distinct processes and by-products of waste generated by the various companies surveyed in Table 1. These flow diagrams offer an exhaustive illustration of each process under investigation, detailing both the input and output components of each operation.

Table 2 collates essential information on each company's primary feedstock, end products, and waste materials. In addition to this, the table also sheds light on the final destination of the waste produced.

Estimation of waste and cellulose pulp generation

The study calculated solid waste generation rates from various raw materials and products to estimate the volume available for cellulose recovery (Table 3). Sugarcane, cassava, and oil palm were found to be less efficient, generating more waste due to their processing methods. Conversely, rice, banana, coffee, and cocoa were more efficient, producing higher yields with most waste comprising husks and shells.

Table 4 presents the estimated solid waste generation and cellulose pulp yield for each crop studied, based on national production figures. Sugarcane processed for sugar production showed the highest levels of waste and cellulose pulp generation among all the crops analyzed.

Discussion

Environmental management, energy consumption, and waste reuse in the surveyed companies

In smaller agro-industrial enterprises, operational sustainability is heavily reliant on the cohesion and partnership among members. The failure of many such enterprises is often due to internal conflicts and lack of strong organizational structures. Regarding health and safety, only a few companies have implemented comprehensive systems, with only Santa Clara and Moliexpress fully enforcing these programs. Notably, none of the companies surveyed have ISO 14001 certification for environmental management, although two of them, Landbar and Indomalsa, have ISO 9001 certification, indicating a commitment to quality management. The energy consumption in these enterprises is minimal, often due to the artisanal nature of their production processes which mainly utilize mechanical energy and gas, with some even reporting no energy costs. A few have low electricity costs due to reliance on artisanal methods, and one company has invested in solar panels to offset energy expenses, reflecting the small scale and low-tech operations prevalent in these firms.

Table 1. Overview of production characteristics and operational details of agricultural and agro-industrial companies in Ucayali region, Peru

Company	Main product	Number of workers	Number of equipment units	Frequency of equipment maintenance	Monthly electricity expense (PEN)
Association of Ecological Products from the San Cristobal de Agua Blanca village (ASCAB)	Honey, panela, *chancaca*	2	5^{n}	After each use	0^{R}
J.M. Ucayali S.A.C (JM UCAYALI)	96° alcohol	54	$20^{n,i}$	Every 4-5 months	43000^{E}
HAVISHA Production and Commercialization of Agricultural Products S.A.C. (PISHCOTA)	Aguardiente, macerated alcohol	4	2^{n}	After each use	200^{E}
Agricultural Association of Cassava from the Valley of Nuevo Tunuya (AAYVNT)	Starch	4	0	None	0
Association of Cassava Producers Santa Catalina (APYSC)	Starch	3	0	None	0
ASERCAMPO S.A.C. Santa Clara Mill (SANTA CLARA)	Rice	22	$20^{n,i}$	5 times per year	20000^{E}
Industries Miller Campo Verde S.A.C. (CAMPO VERDE)	Rice	8	$20^{n,i}$	Daily, weekly, bi-weekly, yearly	15000^{E}
Express Import Export S.A.C. (MOLIEXPRESS)	Rice	8	$11^{n,i}$	Every 4 months	28000^{E}
Landbar Miller E.I.R.L (LANDBAR)	Rice	17	6^{i}	Semiannually	20000^{E}
Aguilar Mill E.I.R.L (AGUILAR)	Rice	11	8^{i}	Monthly	25000^{E}
Agroindustrial Progress Association (AAIPRO)	Banana *chifles*	5	9^{n}	Weekly	0
Cordillera Azul de Ucayali Agrarian Coffee Cooperative Ltd. (CACCAU)	Ground coffee	3	5^{n}	Yearly	45^{E}
Association of Entrepreneurial Women Flor de Boqueron (AMEFB)	Cocoa and chocolate paste	5	8^{n}	Biweekly	250^{E}
Agrarian Cooperative (ASCAH)	Cocoa and chocolate paste	3	4^{n}	None	80^{E}
Central Committee of Agricultural and Livestock Producers of San Alejandro (COCEPASA)	Cocoa and chocolate paste	5	5^{n}	After each use	90^{E}
Agricultural Association of Cacao Producers of Nuevo Ucayali (AAPCNU)	Cocoa and chocolate paste	3	4^{n}	After each use	130^{E}
Industries Oleaginous Monte Alegre S.A. (INDOLMASA)	Palm oil	63	$66^{n,i}$	Weekly	40000^{E}

*Note: S.A.C. stands for *Sociedad Anónima Cerrada*, closed stock company, and E.I.R.L stands for *Empresa Individual de Responsabilidad Limitada*, individual limited liability corporation. They are part of the company's legal names and typically not translated. The source of the equipment is denoted as 'n' for national and 'i' for international. The electricity supply is represented as 'R' for a combination of motor and solar panel power, while 'E' stands for power supplied by the regional electricity distribution company, Electro Ucayali.

Waste reuse

Table 2 shows that sugarcane bagasse and rice husks are utilized for energy recovery through incineration. Furthermore, both moist and dry bagasse derived from sugarcane are repurposed as compost to enrich the soil for sugarcane cultivation. Similarly, cassava peels are utilized as compost for crop nutrition. Rice husks have a wide range of reuse applications, including as an ingredient mixed for small-scale fishing, as feed for pigs, and as bedding in chicken sheds, where they eventually decompose to form organic fertilizer. However, when these husks are not sold or incinerated, they are improperly disposed of in vacant plots. This poses an inconvenience for local residents when strong winds lift and scatter the husk dust.

Banana peels are repurposed as pig feed, and bananas deemed unfit for sale are consumed by workers involved in the selection process, often prepared as boiled green bananas.

Residual coffee husks are also repurposed as fertilizer. Nonetheless, this use has potential environmental implications due to the presence of caffeine, chlorogenic acid, and tannins, substances that can exert significant ecotoxicological effects on aquatic life forms (Marew *et al.*, 2024). Cocoa husks are utilized both as fertilizers and as ingredients in infusions. Meanwhile, residues from palm oil processing can be put to various uses (Mora-Villalobos *et al.*, 2023), such as a filling substance in soil or as material for graveling. The company surveyed utilizes the empty fruit bunches and mesocarp fiber for energy through burning. Furthermore, palm kernel waste, which is also abundant in the study area, can be utilized as a soil filler or for graveling.

The surveyed companies are actively engaged in waste reuse and repurposing initiatives, including composting, selling, and using waste for energy. However, there is room for improvement in managing non-reusable waste and mitigating health and environmental risks associated with waste reuse, highlighting the necessity for enhanced waste management practices.

Table 2. Comparative analysis of feedstock sources, products, main solid wastes, and waste management practices of agro-industrial companies in Ucayali region, Peru

Company	Feedstock	Product	Main solid waste	Waste destination
ASCAB	Sugarcane[o]	Chancaca, panela, molasses[n,i]		Reuse, burning
JM Ucayali	Sugarcane[o]	96° alcohol[l,n]	Sugarcane bagasse	Reuse
PISHCOTA	Sugarcane[o]	Aguardiente, macerated alcohol[l,n]		Reuse
AAYVNT	Cassava[p]	Starch[l,n]	Cassava peel	Reuse
APYSC	Cassava[p]	Starch[l]		Reuse
SANTA CLARA	Rice[f]	Rice, rice dust, milled rice[l,n]		Sale, burning
CAMPO VERDE	Rice[f]	Rice, rice dust, milled rice[l,n]		Sale
MOLIEXPRESS	Rice[f]	Rice, rice dust, milled rice[l]	Rice husk	Sale
LANDBAR	Rice[f]	Rice, rice dust, milled rice[l,n]		Sale
AGUILAR	Rice[f]	Rice, rice dust, milled rice[l]		Sale
AAIPRO	Banana[p]	Banana chifles[l,n]	Banana peels	Reuse
CACCAU	Coffee bean[p]	Ground coffee[l,n]	Coffee husk	Reuse
AMEFB	Dry cacao beans[p]	Cocoa and chocolate paste[l,n]		Reuse
ASCAH	Dry cacao beans[p]	Cocoa and chocolate paste[l]	Cacao husk	Reuse
COCEPASA	Dry cacao beans[f]	Cocoa and chocolate paste[l,n]		Sale
AAPCNU	Dry cacao beans[p]	Cocoa and chocolate paste[l]		Sale
INDOLMASA	Oil palm fruit[f]	Crude palm and palm kernel oil, palm kernel flour[l,n]	Empty fruit bunch	Final disposal

*Note: The feedstock supply is indicated as follows: 'o' signifies sourcing from the company's or association's own land, 'p' denotes sourcing from partners —individuals who own land that is part of the company or association—, and 'f' represents sourcing from farmers, who are third parties not affiliated with the company or association. The distribution channels for the product are represented as 'l' for local, 'n' for national, and 'i' for international.

Estimation of waste and cellulose pulp generation

Table 3 presents the average rates of solid waste generation and feedstock efficiency. As an illustration, for every ton of rice produced, 0,57 tons of rice husks are generated. In comparison, Spada *et al.* (2020) documented a waste generation rate of 0.23 tons per ton of rice produced. This discrepancy could be accounted for by differences in processing efficiency or variations in feedstock quality. For palm oil processing, a yield of 16 % was computed, which aligns with the findings by Dungani *et al.* (2018). This implies that the remainder of the processed materials is waste. Similarly, the yield of cassava processing for starch was recorded at 20 %, which is consistent with the findings of Ekop *et al.* (2019), who reported that every ton of fresh cassava processed results in 680 kg of total waste. However, this study only accounted for waste derived from cassava peels. Cocoa husk makes up 52 % to 75 % of the total wet weight of the fruit (Lubis *et al.*, 2018). However, in this study, cocoa husk represents 16 % of the dry seed weight, suggesting an 84 % yield of waste. The quantity of sugarcane bagasse generated per ton of processed sugarcane aligns with the findings by Toscano Miranda *et al.* (2021), who calculated that each ton of sugarcane results in approximately 270 kg of sugarcane bagasse. However, other studies (Xu *et al.*, 2018) have posited that sugarcane bagasse constitutes up to 50 % of the total volume of processed sugarcane. According to existing literature, the coffee industry generates between 500 kg and 600 kg of husks for every ton of processed coffee (Morales-Martínez *et al.*, 2021), which is in line with this study. However, some research (Dadi *et al.*, 2019) suggests a lower waste generation rate, stating that each ton of coffee produced results in just 1 kg of husk during the drying process.

Policy recommendations for waste management and reuse

The study highlights the potential for sustainable waste management in the agro-industrial sector, suggesting that agro-industrial waste could be repurposed in industries like paper, packaging, textiles, and biofuels. It emphasizes the need for national and local governments to adopt effective waste management and reuse strategies to foster a circular economy. The research underscores the importance of enforcing responsible waste disposal practices and recommends the creation of stringent environmental policies and regulations. These regulations would aim to reduce waste, increase energy efficiency, and promote waste reuse, transforming waste into a valuable resource. Additionally, the study suggests that building the capacity of small and medium-sized enterprises through training in partnership and environmental management is essential for

Table 3. Assessment of feedstock quality, solid waste generation rates, and feedstock conversion efficiency for different agro-industrial products in Ucayali region, Peru

Feedstock	Quality criteria	Product	Waste rate per feedstock	Waste rate per product	Feedstock efficiency
Sugar cane	8-month maturation	Chancaca, panela, liquid sugar,	0.3	6.25	5 %
Sugar cane	8-month maturation	96° alcohol	0.25	4.75	5 %
Sugar cane	8-month maturation	Aguardiente and macerated alcohol	0.33	6.34	5 %
Cassava	Size	Starch	0.40	2.00	20 %
Rice	Broken percentage, color, humidity	Rice and by-products	0.35	0.57	61 %
Banana	Weight	*Chifles*	0.40	0.67	60 %
Coffee beans	Moisture	Roasted coffee	0.42	0.64	65 %
Cocoa beans	Moisture	Cocoa paste and chocolate	0.16	0.20	84 %
Oil palm fruit	Maturation	Crude palm oil, crude palm kernel oil, palm kernel flour	0.26	1.66	16 %

*Note: According to the Kruskal-Wallis test, the results are not statistically significantly different (waste rate per feedstock $p= 0.087$, waste rate per product $p= 0.090$, and feedstock efficiency $p= 0.143$).

Table 4. Estimated solid waste generation and cellulose extraction potential from agricultural residues by Peruvian departments in 2020

Department	Production of each crop (tons)							Potential for cellulose production (tons)						
	Rice	Banana	Oil palm	Cassava	Coffee	Cacao	Sugarcane for sugar	Rice	Banana	Oil palm	Cassava	Coffee	Cacao	Sugarcane for sugar
Amazonas	968027	253865	-	310018	1104658	4544	-	353330	90122	-	125557	386630	1590	-
Ancash	246437	4358	-	10810	-	-	1647057	89950	1547	-	4378	-	-	699999
Apurímac	-	1170	-	1959	-	-	-	-	415	-	793	-	-	-
Arequipa	913624	18	-	690	-	-	110175	333473	6	-	279	-	-	46824
Ayacucho	108	2624	-	25335	65971	6175	-	39	932	-	10261	23090	2161	-
Cajamarca	378907	107866	-	128575	1655517	1581	-	138301	38293	-	52073	579431	553	-
Cusco	5635	76768	-	82261	688294	9740	-	2057	27253	-	33316	240903	3409	-
Huancavelica	-	3056	-	-	-	-	-	-	1085	-	-	-	-	-
Huánuco	90116	595029	62601	157267	286581	16834	-	32892	211235	20658	63693	100303	5892	-
Ica	-	6955	-	19010	-	-	-	-	2469	-	7699			-
Junín	4292	563560	-	291986	1912937	31668	-	1567	200064	-	118254	669528	11084	-
La Libertad	784026	35704	-	44969	5012	43	8609407	286169	12675	-	18212	1754	15	3658998
Lambayeque	1133060	40288	-	10982	34603	138	4177064	413567	14302	-	4448	12111	48	1775252
Lima	19	9757	-	81765	-	-	2882211	7	3464	-	33115	-	-	1224940
Loreto	163347	731173	191949	1134089	1347	665	-	59 622	259566	63343	459306	471	233	-
Madre de Dios	22205	94750	-	55405	520	1605	-	8105	33636	-	22439	182	562	-
Moquegua	-	4	-	-	-	-	-	-	1	-	-	-	-	-
Pasco	4985	210880	-	146819	347558	5012	-	1820	74863	-	59462	121645	1754	-
Piura	1210024	916823	-	12746	96903	2129	705282	441659	325472	-	5162	33916	745	299745
Puno	456	30344	-	113400	190152	728	-	167	10772	-	45927	66553	255	-
San Martín	1924025	1088938	705036	294787	2369250	63085	-	702269	386573	232662	119389	829238	22080	-
Tacna	-	60	-	-	-	-	-	-	21	-	-	-	-	-
Tumbes	201609	346349	-	12704	-	831	-	73587	122954	-	5145	-	291	-
Ucayali	163184	862636	886987	283111	319437	21616	-	59562	306236	292706	114660	111803	7565	-
National TOTAL	1215470	938020	310250	512295	1214599	25257	2948342	443647	332997	102382	207479	425110	8840	1253045

*Note: The data for each crop's production corresponds to the year 2020 and is sourced from the Integrated System of Agricultural Statistics of the Peruvian Ministry of Agrarian Development and Risk (Midagri, 2021). The potential for cellulose production was calculated with the following figures: between 40 % and 45 % in sugarcane (Singh *et al.*, 2022), 35 % in coffee husk (Janissen and Huynh, 2018), 40.5 % in cassava husk (Widiarto *et al.*, 2019), between 12 % and 59 % in banana husk (Tibolla *et al.*, 2019), 35 % in cocoa husk (Lubis *et al.*, 2018), between 33 % and 40 % in rice husk (Gao *et al.*, 2018), and 33 % oil palm stalk (Neyra-Vasquez *et al.*, 2022).

implementing sustainable practices and achieving a more sustainable future in the agro-industrial sector.

While the primary focus of this study is on the extraction of cellulose for biodegradable packaging, recognizing the broader potential of agro-industrial waste can contribute significantly to sustainability efforts in the region. In addition to cellulose extraction, the study recommends exploring alternative waste valorization strategies for agro-industrial waste to maximize its potential. For instance, sugarcane bagasse and rice husks can be processed for biochar for soil enrichment or for bioenergy, such as biofuels, or biogas. Cassava peels, rich in starch, can be processed for bioplastics or for biogas production. Coffee and cocoa husks, which contain bioactive compounds, can be utilized in the pharmaceutical and cosmetic sectors, adding value to these by-products. Bananas peels, in addition, can be processed for use in animals' supplements, or in pectin extraction for use in foods. The implementation of such options would enhance resource efficiency, create new economic opportunities, and significantly reduce environmental impacts, towards a more sustainable and circular agro-industrial economy in the region.

Conclusions

This research presents a method to manage solid waste in the agro-industry by quantifying the waste from seven crops and estimating the potential cellulose yield for biodegradable packaging.

It highlights the opportunity to reduce environmental impact and foster sustainable businesses through effective waste utilization, particularly for cellulose extraction.

Despite some waste reuse practices, the study identifies issues related to the disposal of non-reusable waste and variable energy use, particularly among smaller firms. It suggests the need for standardized waste management and specialized training programs to improve practices in small and medium-sized enterprises.

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