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Technological route for the agro-industrial development of the province of Pastaza based on the valorization of agricultural, livestock, and forest resources

Ruta tecnológica para el desarrollo agroindustrial de la provincia de Pastaza basada en la valorización de los recursos agrícolas, pecuarios y forestales

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KEYWORDS

Keywords: Sustainable agro-industry; bioeconomy; biorefinery; technological integration; resource prioritization; agroindustrial processes; local resources.

Palabras clave: Agroindustria sostenible; bioeconomía; biorrefinería; integración tecnológica; jerarquización de recursos; procesos agroindustriales; recursos locales.

ABSTRACT: The study addresses the need to structure technological routes in the province of Pastaza, where the lack of planning has limited agro-industrial development. Through a technical and objective prioritization, agricultural, livestock, and forestry resources with the highest transformation potential were selected, ensuring their valorization within efficient and sustainable production systems. The methodology was based on the grouping of technologies by sector, establishing selection criteria grounded in production volume, economic value, transformation potential, and environmental sustainability. Applicable technologies were identified for sugarcane, milk, and pigüe, considering biorefinery processes, waste utilization, and the optimization of production routes through P-Graph. The results indicate that the province produces 10,201 tons of sugarcane annually, 8,471 liters of milk daily, and has a forest cover of 749,633 hectares, demonstrating the potential of these resources for bioethanol production, biofuels, dairy derivatives, and kraft pulp. It is concluded that the integration of these technological routes contributes to productive diversification, the strengthening of the local bioeconomy, and agro-industrial sustainability. However, the adoption of these technologies faces challenges related to investment, infrastructure, and market acceptance. It is advisable to conduct experimental validation of the processes and to develop strategies that promote their implementation, ensuring a positive impact on the competitiveness of the agro-industrial sector and the efficient management of resources in Pastaza.

RESUMEN: El estudio aborda la necesidad de estructurar rutas tecnológicas en la provincia de Pastaza, donde la falta de planificación ha limitado el desarrollo agroindustrial. Mediante una jerarquización técnica y objetiva, se priorizan los recursos agrícolas, pecuarios y forestales con mayor potencial de transformación, asegurando su valorización en sistemas productivos eficientes y sostenibles. La metodología se basa en la agrupación de tecnologías por sector, estableciendo criterios de selección fundamentados en volumen de producción, valor económico, potencial de transformación y sostenibilidad ambiental. Se identifican tecnologías aplicables a la caña de azúcar, la leche y el pigüe, considerando procesos de biorrefinería, aprovechamiento de residuos y optimización de rutas productivas mediante P-Graph. Los resultados evidencian que la provincia cuenta con 10,201 toneladas de caña de azúcar anuales, 8,471 litros diarios de leche y una cobertura forestal de 749,633 hectáreas, mostrando el potencial de estos recursos en la producción de bioetanol, biocombustibles, derivados lácteos y pulpa kraft. Se concluye que la integración de estas rutas tecnológicas contribuye a la diversificación productiva, el fortalecimiento de la bioeconomía local y la sostenibilidad agroindustrial. No obstante, la adopción de estas tecnologías enfrenta desafíos relacionados con inversión, infraestructura y aceptación en el mercado. Se recomienda la validación experimental de los procesos y el desarrollo de estrategias que fomenten su implementación, asegurando un impacto positivo en la competitividad del sector agroindustrial y en la gestión eficiente de los recursos en Pastaza.

1 Introduction

The agricultural and industrial sectors contribute approximately 4% and 28% to the global gross domestic product (GDP), respectively [1]. It is estimated that global food demand will increase by 35% to 56% by 2050 [2]. Simultaneously, food processing generates around 1.3 million tons of waste annually, with Europe and North America recording a high per capita production of between 280 and 300 kg [3]. This situation highlights the need to implement optimization superstructures in agro-industrial production and distribution to minimize supply chain losses, optimize input utilization, and enhance environmental sustainability [4]. Such strategies are essential to ensuring food security and improving the competitiveness of agro-industrial markets [5].

In middle-income countries such as Ecuador, the agro-industrial sector contributes more than 30% of the manufacturing value added [6]. However, in the province of Pastaza, the wealth of biodiversity and the availability of raw materials have not driven agro-industrial development due to the absence of established technological routes. Despite being the largest province and hosting approximately 20% of the country’s natural forests [7], its use of sustainable production systems remains limited. Among the main available raw materials are sugarcane, *Piptocoma discolor* (pigüe), and milk, along with the residues generated by these three resources. They were chosen because these residues hold significant potential for utilization through biorefinery processes [8; 9]. To achieve this, it is necessary to establish a circular economy strategy encompassing the production and transformation of raw materials as well as the valorization of their residues through biotechnological and industrial processes [10-12]. In this context, identifying and analyzing the applicable technological routes for raw materials and their derivatives in the region is essential to strengthening agro-industrial development in Pastaza.

Pastaza, the largest province in Ecuador, has historically based its economy on oil exploitation and subsistence agriculture, characterized by traditional and artisanal practices, including the production of *panela* and *aguardiente* [13]. Therefore, it is necessary to identify key operations and unit processes in the agro-industrial sector to foster regional development. Moreover, given the province's high biodiversity, it is essential to select technologies suited to local climatic and soil conditions, supporting innovation and the development of sustainable production systems that respect the Amazonian ecosystem [14]. Pastaza's economy relies on two types of primary production: *chakras*, which are small agricultural plots focused on subsistence, and Agricultural Production Units (APUs). Adapting and optimizing production methods is crucial to promoting a more sustainable and efficient development model. Additionally, small and medium-sized enterprises in the region base their decisions on experience rather than on verifying the effectiveness of their processes, highlighting the need for evidence-based approaches in production management.

The main issue in the region is the absence of structured technological routes for efficiently transforming local raw materials. The lack of integration between sustainability, agro-industry, and technology has hindered sector development [15], resulting in low productivity and dependence on informal markets. Additionally, the limited standardization and deficiencies in agro-industrial planning have restricted the added value of products [16], affecting their competitiveness at both national and international levels. The inadequate technological infrastructure perpetuates traditional production models [17] and limits productive diversification. Given this situation, it is essential to design technological routes that establish a more efficient and sustainable system.

The Analytic Hierarchy Process (AHP), Strengths, Weaknesses, Opportunities, and Threats (SWOT), Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), and Preference Ranking Organization Method for Enrichment Evaluation (PROMETHEE) have been widely used in multi-criteria decision-making, applied in the planning, evaluation, and optimization of alternatives across various sectors [18]. However, superstructure-based optimization remains essential in process engineering due to its capability to model and optimize advanced industrial configurations [19]. This approach enables the integration of optimization rules into pre-formulated superstructures, leveraging specialized computational tools to enhance the efficiency of industrial processes [20].

The P-Graph framework is a computational tool developed to facilitate the design, modeling, and optimization of complex process networks using combinatorial principles. This framework generates all possible system configurations, considering raw materials, products, and technical constraints, allowing for the selection of the most resource and cost-efficient option [21]. Its applications are extensive, encompassing the optimization of industrial, energy, food, and water treatment systems [22]. Additionally, P-Graph contributes to the design of sustainable processes by minimizing environmental impact and maximizing resource efficiency [23]. The P-Graph-based design involves generating feasible structures, evaluating them based on economic and environmental criteria, and reducing combinatorial complexity through advanced algorithms [24].

Given the absence of technological routes in the province of Pastaza, there is a need to identify strategies that enable the transformation of local raw materials, fostering sustainability and agro-industrial development. How can the integration of sustainable technologies maximize the utilization of agricultural, livestock, and forestry resources in the province of Pastaza? In response to this question, the objective of the study was to design a technological route for the agro-industrial development of the province of Pastaza, based on the valorization of agricultural, livestock, and forestry resources.

2 Methodology

2.1 Location of the study area

The research was developed in the province of Pastaza, an area of agricultural, livestock, and forestry production. This region, with an area of 29,643.33 km^2, is divided into four cantons: Pastaza, Mera, Santa Clara, and Arajuno, and comprises 21 parishes, namely Puyo, Tarqui, Fátima, Teniente Hugo Ortiz, Diez de Agosto, El Triunfo, Veracruz, Pomona, Canelos, Simón Bolívar, Sarayacu, Montalvo, Río Tigre, Río Corrientes, Mera, Shell, Madre Tierra, Santa Clara, San José, Arajuno, and Curaray [25]. The region is characterized by a warm tropical climate, with temperatures ranging between 18 and 33°C, a relative humidity of around 87.83%, and annual precipitation that varies between 2,000 and 4,000 mm [26]. Figure 1 shows the borders and land use of the province. According to the reported data, the province has 5,263 APUs [25].

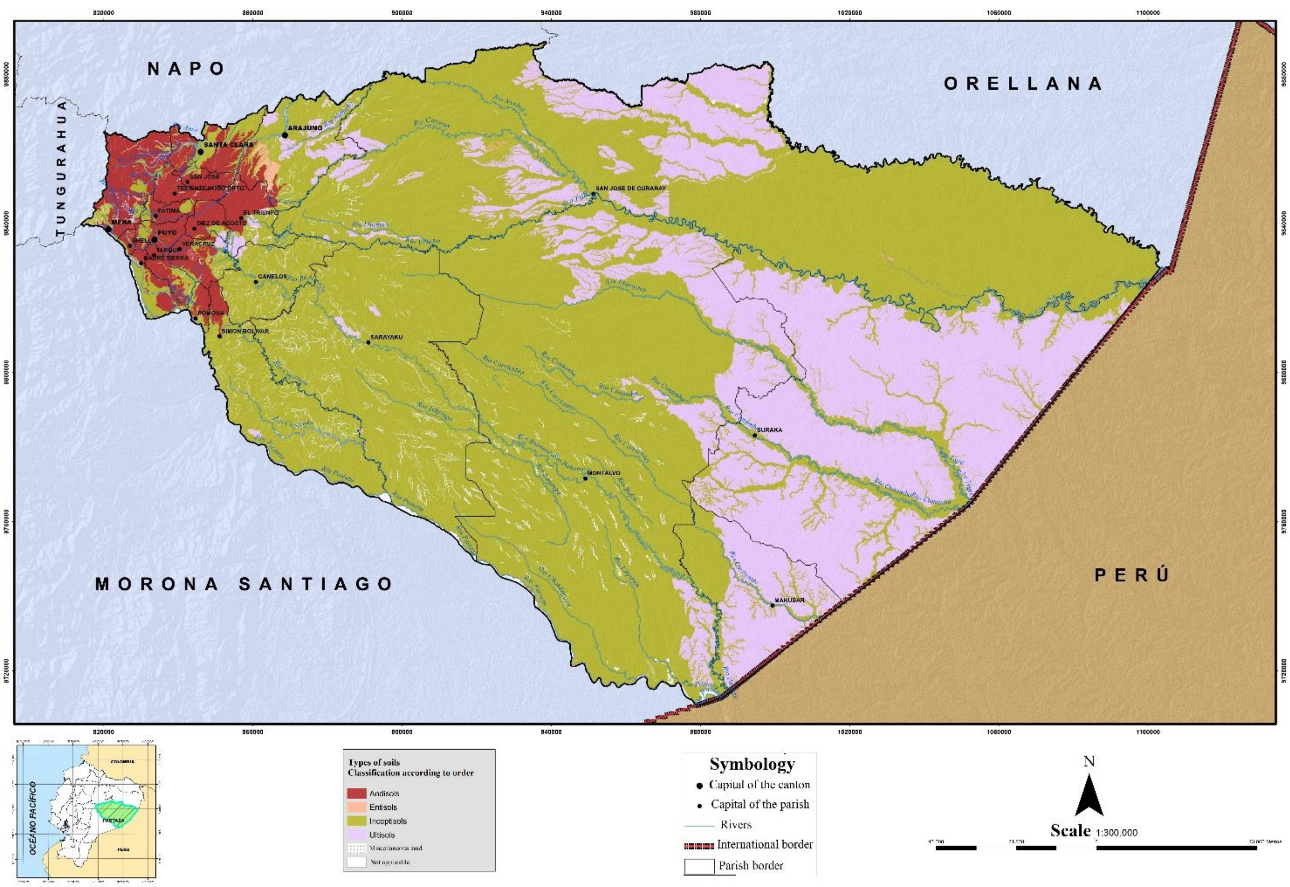


Figure 1 Land use in the province of Pastaza
Source: [25]

2.2 Databases used

The primary databases used were Ecuador's Agricultural Public Information System (SIPA), the Ecuadorian Ministry of Agriculture and Livestock (MAG), the Decentralized Autonomous Government of the Province of Pastaza (GADPP), and the Territorial Development and Planning Plan (PDOT).

Additionally, information was supplemented with scientific literature available on Google Scholar and ScienceDirect to strengthen the analysis with previous studies and trends in the agro-industry.
The selection of these databases was based on their ability to provide information on agricultural and forestry production in Pastaza, the territorial distribution of resources, and the region's sustainable development policies. Each data source was chosen by considering its level of update frequency and applicability in designing technological routes for raw material utilization (Table 1).
The data extracted from SIPA and MAG correspond to official agricultural sector records, with periodic updates reflecting the evolution of production and land use in Ecuador. Meanwhile, information from GADPP and PDOT provides a territorial and strategic framework to align technological proposals with local development plans.

Table 1. Databases and their application in research.

Database	Description	Relevance in Research	Update Frequency
SIPA	Provides data on agricultural production and agricultural waste at national and regional levels.	Enables the assessment of production volume and the transformation potential of raw materials in Pastaza.	Annual
MAG	Records statistics on agricultural and livestock production and land use in Ecuador.	Provides official data for identifying production trends and agro-industrial opportunities.	Periodic
GADPP	Contains geographic, administrative, and territorial planning information for the province.	Facilitates territorial analysis for technological route planning and resource utilization.	Variable (according to planning)
PDOT	Defines strategies and guidelines for sustainable development in the province.	Ensures that technological proposals align with regional development policies.	Every 4 years
Google Scholar and ScienceDirect	Repositories of scientific literature on agro-industry and sustainability.	They complement the analysis with previous studies, technological trends, and theoretical frameworks.	Continuous

2.3 Sequential stages for the technological route

The technological route for Pastaza was determined using three stages with sequence behavior similar to that presented by [15]. The first step consists of prioritizing agricultural, livestock, and forestry production and agro-industrial waste, the second step is the matrix of agro-industrial products, technologies, and raw materials, and the last stage is the development of the technological route (Figure 2).

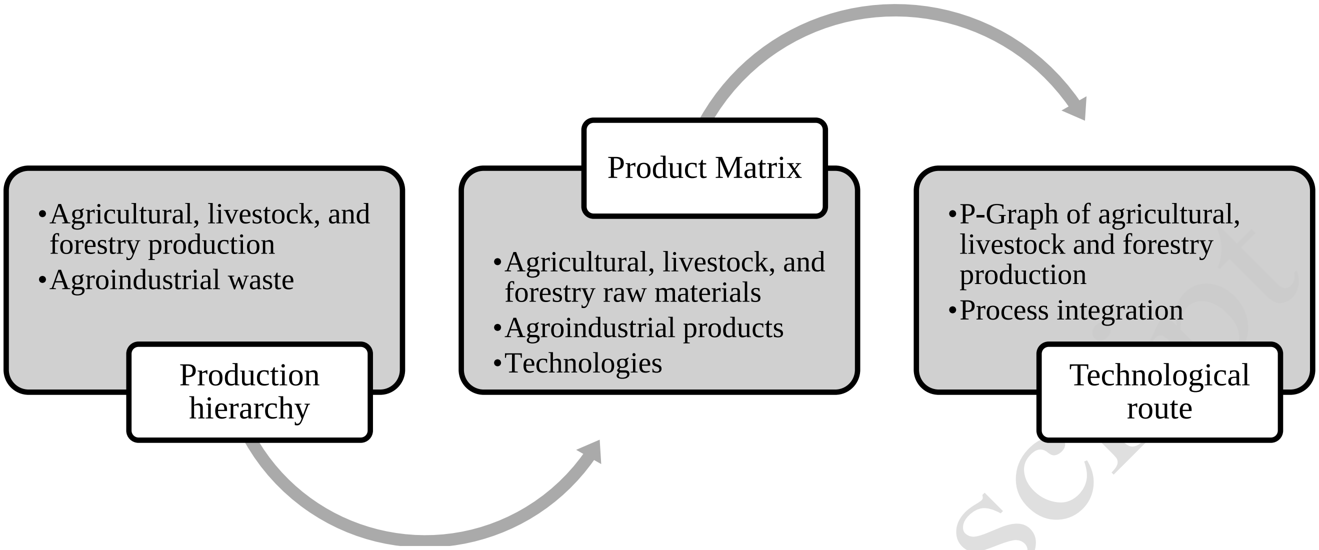


Figure 2. Sequential stages for choosing the technological route

2.3.1 Phase 1. Hierarchization of agricultural, forestry, and agro-industrial waste production in the province

A process was established for the selection of raw materials in the province of Pastaza, carried out through land use analysis using data from SIPA and MAG. Based on these data, the main agricultural, livestock, and forestry products were identified according to their production volume and economic relevance. However, to ensure an objective selection, a multi-criteria decision-making method was implemented, combining the AHP and the TOPSIS method with the aim of prioritizing raw materials with the highest agro-industrial potential. The selection of raw materials was based on the following criteria, weighted according to their importance within the agro-industrial context of the province (Table 2).

Table 2. Weighted criteria in technological routes.

Criterion	Description	Weight (%)	Reference
Production volume	Amount of raw material available annually	30	[27; 28]
Economic value	Contribution of the product to the agro-industrial sector	20	[29; 30]
Transformation potential	Possibility of generating added value through technologies	25	[10; 31]
Environmental sustainability	Environmental impact and potential for waste utilization	15	[32; 33]
Market demand	Commercial potential and internal and external demand	10	[15]

The main raw materials identified were sugarcane, milk, and pigüe. Subsequently, weights were assigned to the criteria through pairwise comparison in AHP, and TOPSIS was applied using historical production and commercialization data to evaluate their performance. Finally, the raw materials were ranked based on their agro-industrial feasibility.

2.3.2 Phase 2. Development of the matrix of agro-industrial products, technologies, and raw materials of the province

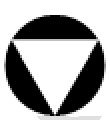
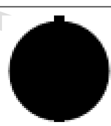
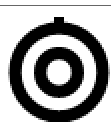
The second phase included developing matrices that connect the selected raw materials with the proposed technologies for their transformation into agro-industrial products. This process first involved an analysis of provincial production to prioritize raw materials. Then, specific technologies were proposed that would allow raw materials to be efficiently converted into value-added products with a focus on sustainability. The matrices systematically integrated the technological options for agricultural, livestock, and forestry sectors, reflecting an interdisciplinary design that aligns the productive capacities of the province with market trends and needs [34].

2.3.3 Phase 3. Creation of the technological route for agroindustrial development in the province

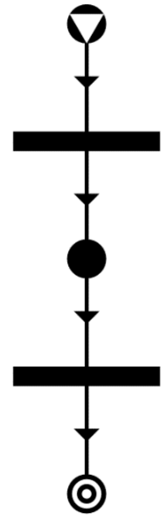
In Phase 3 of the methodology, the structuring of raw materials and previously prioritized technologies was carried out using P-Graph version 5.2.5.0. This software enabled the mapping and visualization of complex interactions between various agricultural, livestock, and forestry production routes, ensuring a comprehensive planning of technological processes. P-Graph also facilitated the identification of synergies between sectors and the optimization of waste utilization strategies, with a focus on environmental sustainability.

While other tools, such as Python and R Studio, allow for agro-industrial process modeling, P-Graph offers key advantages, including the optimization of production and transformation networks [35]. Unlike traditional methods based on manual programming, P-Graph incorporates specific algorithms for the synthesis and analysis of process superstructures, enabling a more intuitive and efficient representation of production networks. Additionally, it facilitates the identification of potential synergies and redundancies in production processes, clearly visualizing the integration of different routes. Finally, another advantage of P-Graph is its ability to ensure the reproducibility of results through the standardization of modeling structures. The generated models can be replicated with different datasets without altering the optimization logic.

Table 3. P-Graph symbols

Symbol	Description	Diagram
	Raw material	
	Intermediate material	
	Product	

Operating units



Studies by [36] have demonstrated the applicability of P-Graph in optimizing biomass supply networks and configuring integrated biorefineries. Specifically, [37] developed a P-Graph-based model for the economic optimization of supply chains, reducing greenhouse gas emissions while considering seasonal variability in biomass availability. Meanwhile, [38] applied P-Graph to generate optimal biorefinery configurations, utilizing agricultural waste as raw material.

3 Results and Discussion

3.1 Hierarchy of agricultural, forestry, and agro-industrial waste production in the province

The analysis of the SIPA data from 2023 reveals that in the province of Pastaza, the majority of the land, amounting to 749,633 hectares (ha), is allocated to forests and woods, reflecting a vast forest coverage. Cultivated pastures and other uses account for 38,043 and 30,653 ha, respectively, indicating significant agricultural and livestock activities. Permanent crops and fallow lands occupy smaller portions of 3,059 and 1,861 ha, respectively. Meanwhile, temporary crops and fallow lands with natural pastures cover the smallest areas: 1,188 and 551 ha. These data show a dominance of forest conservation and sustainable use in Pastaza, with a moderate presence of agriculture and livestock. According to [39], the soils in this region are characterized by their low nutritional content and lower fertility compared to lands in other provinces that are more suitable for agricultural development.

3.1.1 Agricultural production

Sugarcane is the most produced product, standing at 10,201 tons in 2023, followed by plantain (3,064 tons). Bananas, cassava, and dry hard corn are also produced on a significant scale at 1,394, 848, and 111 tons, respectively. Cocoa, a high-value crop, has a more modest production of 46 tons, and lemons (fresh fruit) are produced on an ever smaller scale (13 tons) Notably, coffee and pineapples (fresh fruit) have insignificant production figures [40]. The province of Pastaza produces 54.4% of the sugarcane in the Ecuadorian Amazon, with approximately 65% of this production destined for the making of panela and 35% for alcohol production [41]. The Economically Active Population (EAP) of the region primarily focuses on this crop, particularly highlighting the Limeña variety, which is marketed as fruit [25].

Panela production in Pastaza is considered more artisanal than industrial. The reasons for this characterization vary from state policies to quality criteria. Competition with agro-industrial derivatives is virtually nonexistent against white sugar produced in sugar mills, demonstrating a lack of technification and process parameter control as well as a lack of awareness of the nutritional and medicinal benefits of panela [42]. According to [25], there are about 6,354 hectares dedicated to sugarcane cultivation in the province. Technological processes show a notable delay with the use of inappropriate techniques and tools, which relegates this agro-industry to a category of subsistence and tradition, focused on the production of two main products: panela and aguardiente, as described in Table 2.

Table 4**.** Traditional agro-industry microenterprises

Main Activity	Total Annual Income	Total Companies
Production of panela	$930,153.33	82
Production of sugarcane aguardiente	$321,750.00	22
Total	$1,251,903.33	104

Source: [25].

3.1.2 Livestock production

According to figures for 2023 [40], beef cattle dominate with 15,501 heads, constituting the vast majority of livestock in the province. Pigs also have a significant presence with 2,441 heads. Horses total 874, while mules account for only a minuscule number with 4 heads. The total of 18,821 heads of livestock highlights the predominance of beef cattle in Pastaza's agricultural sector.

Dairy production in the province's farms must come from healthy animals under acceptable conditions. Stakeholders involved in the value chain should be an integral part of the quality management and food safety system [43]. The total daily dairy production in Pastaza is 8,471 liters. The majority of the milk (6,148) liters is sold in liquid form. A small but significant amount (967 liters) is processed on the same premises where it is produced. This may include activities such as pasteurization, cheese making, or yogurt production. A smaller portion, 118 liters, is designated for direct consumption on the premises by workers and their families or for feeding animals.

The dynamics of the dairy sector in Pastaza are experiencing a notable boost with major companies in the country, such as Rancherito, investing in infrastructure like cooling tanks to store locally produced milk. These industries ensure the purchase of milk at prices defined by the government, thereby encouraging local producers to maintain high-quality standards in their livestock operations.

However, according to [25], the agro-industry in Pastaza is characterized by a division between manufacturing and traditional agro-industry, and in the national context, it only contributes 4.07% of the production. Despite the lack of an industrial park or benchmark brands, and with most companies classified as microenterprises, the province focuses on meeting the needs of the local market.

3.1.3 Forest production

In Pastaza, forestry exploitation and agricultural expansion, along with illegal logging and oil exploitation, have contributed to deforestation and the replacement of wooded areas, negatively affecting Indigenous communities. According to [25], Pastaza has 521,080.96 hectares of land suitable for forestry. The species *Piptocoma discolor*, commonly known as pigüe, is a softwood native to the Amazon that thrives in secondary forests in the province of Pastaza. It exhibits a 95% germination rate and an impressive 95.8% survival rate after transplantation, reaching 3.21 meters in height and 7.2 cm in diameter in just 2.5 years [44]. Due to its use in the manufacture of stretchers and fruit transport boxes, pigüe is economically valuable and abundant thanks to its integration into fallow practices [45]. Pastaza's 2,791,289.07 m^3 of natural forest represents 22.10% of the provincial total and is the country's leader in forest area [40]. The Ecuadorian Environment Ministry has authorized the use of 2,616.53 m^3 of pigüe trees from 2021.

3.2 Matrix of agroindustrial products, technologies, and raw materials of the province

In Ecuador, starting in 2007, the construction of the national development plan was proposed, focusing on the transformation of the productive matrix. This includes forming organizations to produce certain goods, products, or services in a timely manner and with an established price that not only includes the technical or economic processes but also social, political, and cultural aspects involving all actors [46]. It must be made clear that industrialization represents a badge of progress so that a developed country maintains sustainable economic growth that will improve the living conditions of its inhabitants. Productivity is reflected in higher incomes for the productive transformation of actors within the economy. Popular, supportive, and private sectors are key, as is government support through incentives, improving competitiveness [47].

3.2.1 Agricultural production matrix

Once the raw materials with the highest commercial importance in the province had been determined, various technologies were established that are already applied and others that are proposed for pilot-scale development to assess their feasibility and sustainability. Sugarcane is one of the main crops in the province, but its production is limited to direct consumption, panela production, and aguardiente. Below are some proposed alternatives for the transformation of this crop into agricultural products (Table 3).

Table 5. Proposed technologies for the hierarchical agricultural technology (AT) in Pastaza

	Cane Juice	Cane Honey	Panela	Ethanol	Biodiesel	Composting	Kraft Pulp	Citric Acid
Sugarcane	AT 1	AT 2	AT 3	AT 4				
Cachaza					AT 5	AT 6		
Bagasse				AT 7			AT 8	AT 9
Cane honey			AT 10	AT 11				

Description of Technologies for Sugarcane:

- Agricultural Technology 1 (Sugarcane Juice)

This process involves the extraction of sugarcane juice using compression techniques to obtain the liquid. It is crucial to apply pre-treatment and post-treatment to maximize juice recovery.

- Agricultural Technology 2 (Cane Honey)

Cane honey is obtained through the concentration of sugarcane juice followed by a cooking process. This energy-rich food is known for its sweet flavor and its extensive use in various culinary preparations.

- Agricultural Technology 3 (Panela)

Panela is produced through processes that include compression, extraction, filtration, clarification, heating, and evaporation of the sugarcane juice. The resulting product is then concentrated and molded to obtain a solid that is high in sugar.

- Agricultural Technology 4 (Ethanol)

Ethanol is produced by extracting juice through compression, followed by a fermentation and distillation process. This alcohol is widely used as fuel and in the chemical industry.

- Agricultural Technology 5 (Biodiesel)

Biodiesel is obtained using the sugarcane byproduct known as cachaza, through a process that includes extraction, evaporation, and transesterification. Ethanol is used to obtain this renewable fuel.

- Agricultural Technology 6 (Composting)

Composting is a technique that utilizes cachaza mixed with other agricultural residues to produce compost rich in nutrients to improve soil quality and crop productivity.

- Agricultural Technology 7 (Ethanol)

Similar to AT 4, this method involves the fermentation and distillation of the sugars present in the raw material to obtain ethyl alcohol.

- Agricultural Technology 8 (Kraft Pulp)

The kraft pulp technology refers to the process of obtaining cellulose pulp from sugarcane bagasse. It involves stages such as debarking, chipping, cooking, bleaching, drying, and molding.

- Agricultural Technology 9 (Citric Acid)

Citric acid is obtained through processes that include filtration, dilution, nutrient addition, sterilization, inoculation, and fermentation. This acid is widely used in the food and pharmaceutical industries.

- Agricultural Technology 10 (Panela)

The panela production process involves the concentration, evaporation, stirring, beating, and molding of sugarcane juice. The final product is a solid that is high in sugar and has a distinctive flavor.

- Agricultural Technology 11 (Ethanol)

Similar to AT 4, this method involves the fermentation and distillation of the sugars present in the raw material to obtain ethyl alcohol.

3.2.2 Livestock production matrix

Livestock production has become increasingly important in Pastaza, particularly in the dairy sector, where traditional processing methods are prevalent. To improve the sector, it is advisable to diversify the range of dairy products on offer and, simultaneously, implement technologies to valorize by-products and waste, such as whey, which currently constitutes a significant source of pollution in cheese factories. These initiatives aim to mitigate the environmental impact of the dairy industry and foster more efficient and sustainable resource management. Table 4 presents the suggested technologies to optimize the dairy production chain in the province.

Table 6. Proposed technologies for the hierarchical livestock technologies (LT) in Pastaza

	UHT Milk	**Cheese**	**Yogurt**	**Milk Candy**	**Butter**	**Ricotta**	**Whey Powder**	**Ethanol**	**Citric Acid**
Milk	LT 1	LT 2	LT 3	LT 4					
Whey						LT 5	LT 6	LT 7	LT 8
Cream					LT 9				

Description of Technologies for Milk

- Livestock Technology 1 (UHT Milk)

A process to ensure milk preservation, this involves the separation and pasteurization of milk through high temperatures for a short period and is known as UHT (Ultra High Temperature) milk.

- Livestock Technology 2 (Cheese)

For cheese production, the process entails milk separation followed by pasteurization and curdling. This includes coagulation, whey separation, and pressing to obtain different varieties of cheese.

- Livestock Technology 3 (Yogurt)

The yogurt-making process involves the separation of milk, followed by pasteurization, cooling, and incubation with bacterial cultures. This results in a fermented dairy product known as yogurt.

- Livestock Technology 4 (Milk Candy)

This process consists of milk separation and pasteurization, followed by concentration through cooking to obtain milk candy (manjar de leche), a thick and sweet product.

- Livestock Technology 5 (Ricotta)

A cooking process with citric acid followed by filtering is used to obtain ricotta. This involves stages of heat treatment, coagulation, whey separation, and pressing to achieve the desired consistency of the final product.

- Livestock Technology 6 (Whey Powder)

This process includes the separation of whey, followed by pasteurization, concentration, and spray drying to obtain whey powder, a product used in the food industry.

- Livestock Technology 7 (Ethanol)

This process involves the enzymatic hydrolysis of whey, followed by fermentation and distillation to produce ethanol, an alcohol used in various industrial applications.

- Livestock Technology 8 (Citric Acid)

This process involves filtration, dilution, nutrient addition, sterilization, inoculation, and fermentation to produce citric acid, a compound used in the food and pharmaceutical industries.

- Livestock Technology 9 (Butter)

This process includes the standardization of milk and the churning of cream with an appropriate level of acidity to produce butter, a widely consumed dairy product.

3.2.3 Forestry production matrix

In recent years, pigüe has been widely studied and is a species from secondary forests that grows and reaches maturity in a short time compared to other species. The raw material is processed to generate benefits. Table 5 shows the technologies for the use of pigüe in the province.

Table 7. Proposed technologies for the hierarchical forestry technologies (FT) for the province of Pastaza

	Pellets	Charcoal	Synthesis Gases (Syngas)	Kraft Pulp	Ethanol
Pigüe	FT 1	FT 2	FT 3	FT 4	
Kraft pulp					FT 5

Description Technologies for Pigüe:

- Forest Technology 1 (Pellets)

This is the mechanical process of chipping and drying the wood chips for subsequent use.

- Forest Technology 2 (Charcoal)

This involves the primary carbonization of the raw material, followed by high-temperature thermal treatment.

- Forest Technology 3 (Syngas)

This is a process involving the drying, pyrolysis, and gasification of biomass to obtain synthesis gases.

- Forest Technology 4 (Kraft Pulp)

This is similar to AT 9.

- Forest Technology 5 (Ethanol)

Lignocellulosic residues can be an important raw material for obtaining bioethanol. For such conversion, glucan through enzymatic hydrolysis is converted to glucose, and subsequently, fermentation to ethanol occurs.

3.3 Creation of the technological route for agro-industrial development in the province

The application of P-Graph in the synthesis of processes involving multi-period operations proves to be an approach that fits the dynamics of the agro-industrial industry, where seasonal factors and demand fluctuations play a crucial role [48]. This allows for the accurate modeling of changes in the load of operational units over different periods while maintaining constant operating conditions within each period.

3.3.1 Technological route for agricultural production

With the information collected, it was determined that sugarcane is the crop with the highest production in the province, standing out for following traditional transformation processes. Despite being the most important crop, it does not compete at the national level and its transformation has been limited to the production of panela and liquor, emblematic products of the region. The proposal suggests expanding the range of products to include compost, kraft pulp, and cane honey, the latter of which offers nutritional properties different from processed sugar, including carbohydrates, minerals, and vitamin B. Ethanol, obtainable from cane honey, bagasse, and citric acid, is an important commercial additive for the food and pharmaceutical industries (Figure 3).

The use of P-Graph to represent the transformation of sugarcane into products, such as ethanol, kraft pulp, compost, and biodiesel from bagasse and cachaza, highlights the importance of optimizing the network structure in terms of costs and environmental sustainability (Figure 3). Through P-Graph, the most favorable network structure can be identified from both an economic and ecological perspective, which is essential for the long-term viability of the agro-industrial industry [49].

The analysis using P-Graph facilitates the integration of processes and potential redundancy in superstructures. Figure 3 identifies that the production of ethanol from bagasse, cachaza, and sugarcane juice involves operations that converge, specifically fermentation and distillation. The integration of these processes, particularly concerning heat flows, emerges as a fundamental strategy to increase energy efficiency and minimize operating costs, as indicated by [50].

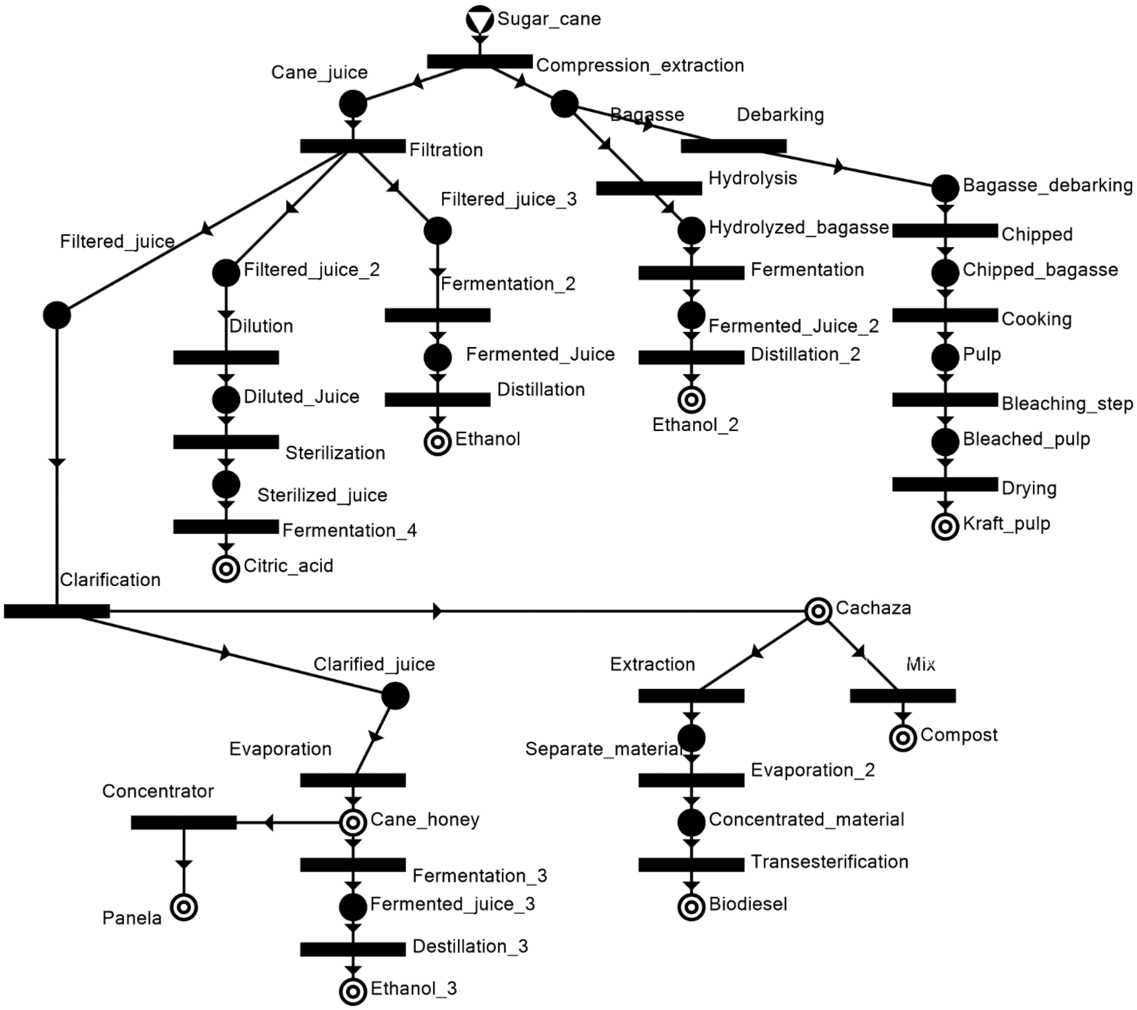


Figure 3 P-Graph of the processes for sugarcane

Although this proposal focuses on the conceptual design of technological routes, it is essential to consider economic, environmental, and social feasibility in future implementation phases. Recent studies indicate that bioethanol production from sugarcane bagasse can be optimized through efficient pretreatments, releasing up to 4.0 g/L of fermentable glucose and improving profitability [51]. According to [52], bioethanol produced from molasses exhibited emissions of 3.26 kg CO_2-eq/MJ and an energy consumption of 1.25 MJ/MJ, demonstrating greater economic viability in scenarios with 26.5% renewable energy.

From an environmental perspective, the annual production of sugarcane bagasse is estimated to reach 513 million tons globally, with an energy potential of up to 4.3 EJ, representing 6.8% of the global bioenergy supply, positioning it as a significant renewable resource [53]. Regarding the social dimension, product diversification, including bioethanol and compost, promotes sustainability, fosters job creation, and strengthens local economies in the province of Pastaza [54].

3.3.2 Technological route for livestock production

Milk represents one of the most important items at the national level, and in Pastaza, dairy production is one of the most economically significant sectors. This is due to agricultural producers shifting their productive activities by expanding agricultural and livestock estates, as is the case with cattle farming.

The analysis highlights the importance of diversifying dairy products and utilizing by-products, especially whey, whose improper disposal causes significant environmental impacts. UHT sterilization is proposed to extend the shelf life of milk, complementing the already popular HTST milk and the local acceptance of traditional products such as cheese and yogurt. Additionally, innovation through the production of manjar de leche (milk candy) is suggested, which could increase market profitability. Standardizing processes is essential, viewing cream as a resource that is not yet fully exploited, either for direct sale or butter production. Regarding cheese, it represents 80% of the volume per liter of processed milk, providing a basis for the production of ricotta, whey powder, ethanol, and citric acid, highlighting the potential of these by-products in agricultural use and environmental sustainability.

In the field of dairy production, P-Graph has the potential to optimize the sequence of separation operations, which are crucial in processing milk to obtain products such as cheese, whey, and yogurt. Thus, authors such as [55] mention that separation networks using P-Graph can be designed to minimize operating and capital costs as well as reduce energy consumption. In Figure 4, operations such as pasteurization, coagulation, and whey drying are key steps in which efficiency can be improved. Furthermore, the separation of whey and curd can be optimized to increase cheese yield and minimize waste whey, which is beneficial not only from a cost perspective but also for the environmental management of by-products.

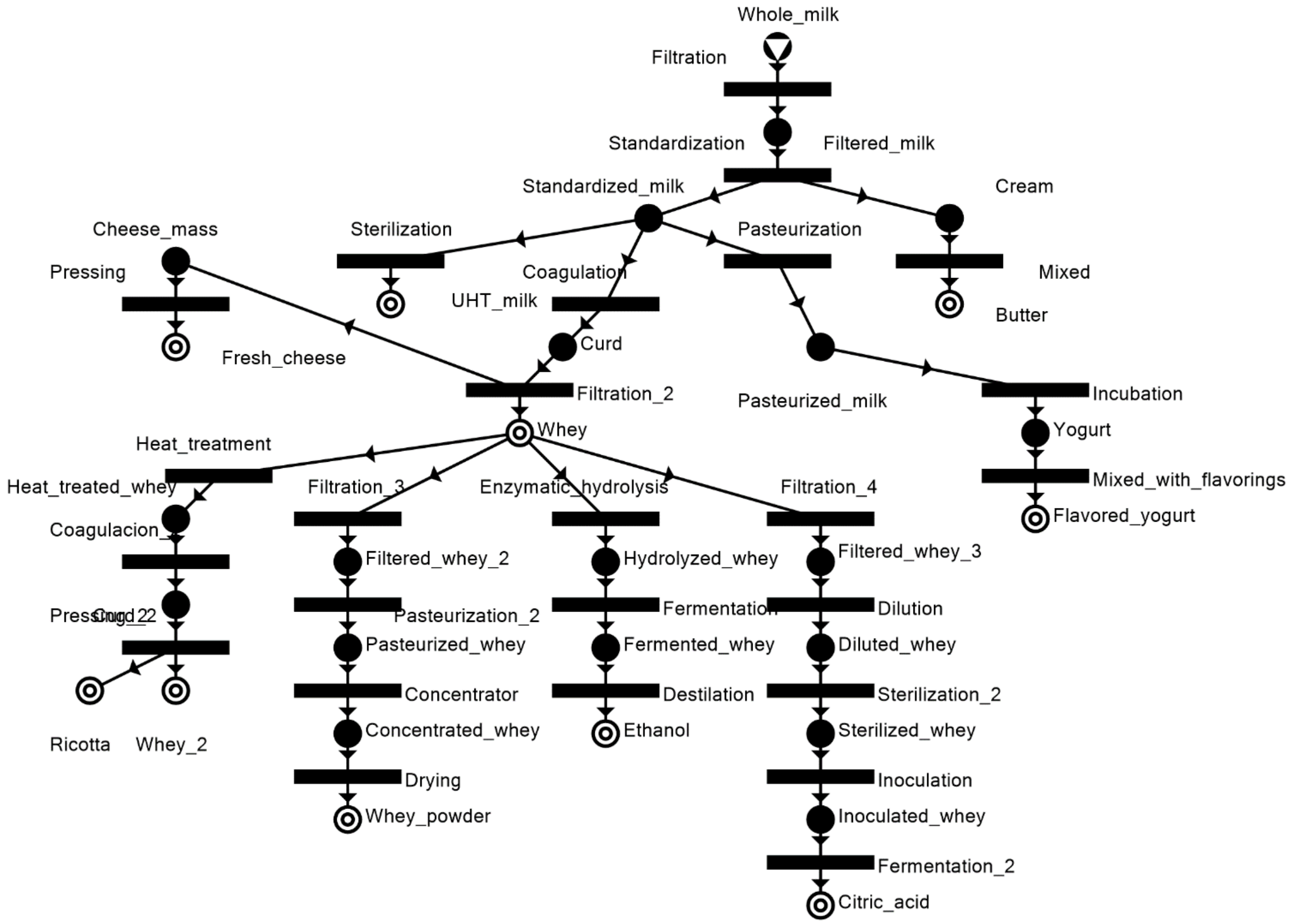


Figure 4 P-Graph of processes for milk

Authors such as [56] highlight the relevance of P-Graph models in configuring adaptable and sustainable energy systems over various periods. This flexibility is crucial in the dairy industry, where production must adjust to seasonality and market volatility. Implementing a P-Graph model can be a transformative solution for the dairy industry, not only allowing a dynamic response to the variability of raw materials and demand fluctuations but also optimizing operational efficiency. This could result in a more resilient dairy production chain that effectively manages the inherent uncertainties of the sector, maintaining continuity in delivering high-quality dairy products to consumers.

The diversification of dairy products and the valorization of by-products, such as whey, represent economic opportunities for the sector in Pastaza. For every kilogram of cheese produced, approximately 9 liters of whey are generated, which can be transformed into value-added products such as whey powder, bioethanol, or citric acid [57]. From an environmental perspective, whey contains up to 48% lactose and 2.6% protein, which, if not properly managed, could significantly contribute to water pollution. However, its utilization through anaerobic digestion processes enables biogas production, reducing organic load and promoting process sustainability [58]. In the social domain, diversification strategies in rural farms have been proven to enhance financial stability and create employment, as evidenced by experiences in agricultural regions of Switzerland [59].

3.3.3 Technological route of forestry production

In the province of Pastaza, according to [25], an area of 521,080.96 hectares has been classified as suitable for forestry. This implies that these areas are appropriate for forestry development projects, where species with optimal yields are selected to provide raw materials from plantations, rather than resorting to the extraction of resources from native forests.

It has been identified that pigüe has greater technological relevance than balsa wood, highlighting its potential beyond the manufacture of fruit boxes and pallets, which has been its predominant use so far. By considering pigüe as plant biomass, its viability as a source of renewable energy is revealed, especially if productive reforestation projects are implemented with the aim of obtaining raw materials for energy. The wood waste from pigüe, currently underutilized, could be transformed into densified solid biofuels, such as pellets, or into kraft pulp, opening up a new pathway for paper production, given its composition. Authors such as [35] investigated the application of the P-Graph approach for creating resource conservation networks (RCN) in industrial contexts with a particular emphasis on the direct reuse and recycling of resources. This aspect is especially pertinent in the forestry industry, which is notorious for producing a variety of by-products and waste. Figure 5 illustrates the processing of biomass into products such as charcoal, syngas, and paper pulp. In this context, P-Graph can maximize the utilization of by-products and minimize waste, contributing to more sustainable operations and a more circular economy.

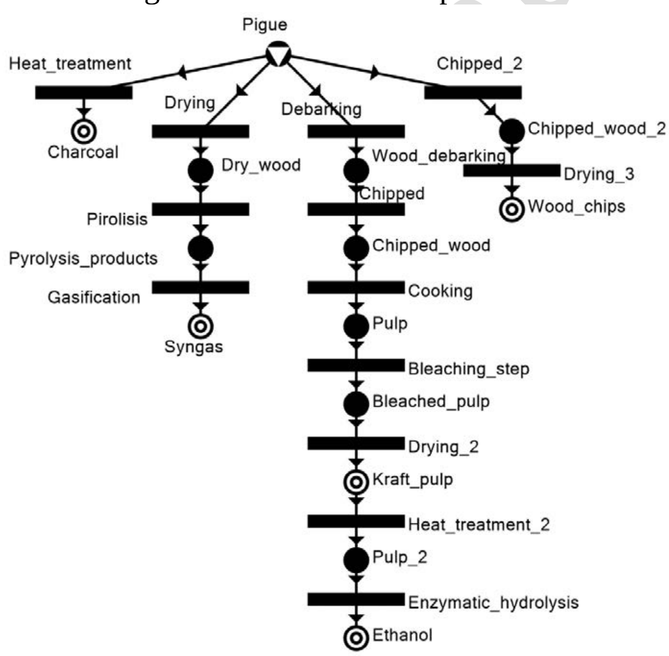


Figure 5 P-Graph of the processes for pigüe

In the study by [48], P-Graph was employed for operational units with flexible input ratios, which is applicable to ethanol production, where the enzymatic hydrolysis of pulp requires adjustments based on the quality and quantity of available raw material (Figure 5). In the forestry industry, implementing a P-Graph system allows for the adaptation of ethanol production operations to handle fluctuations in wood quality and market conditions, ensuring efficient and consistent production.

The utilization of pigüe in Pastaza for the production of solid biofuels and derivative products represents a strategic option for diversifying forestry production. From an economic perspective, wood residue gasification can achieve carbon conversion rates of up to 75.8% at 800°C with an equivalence ratio of 0.15, optimizing energy yield [60]. From an environmental standpoint, using residual forest biomass instead of open burning could reduce CO_2 emissions by up to 40,909 equivalent tons per year in communities dependent on fossil fuels [61]. Additionally, the organosolv pretreatment for ethanol production from lignocellulosic biomass allows for up to 90% lignin removal, enhancing enzymatic hydrolysis efficiency and optimizing the conversion process [62]. Socially, implementing these technologies reduces pressure on native forests and promotes local employment creation in activities related to the collection, processing, and commercialization of forestry products. While this proposal focuses on the technological structuring of processes, it acknowledges the importance of evaluating comprehensive feasibility in future research to ensure the sector's sustainability in the province of Pastaza.

3.3.4 Integration of agricultural, livestock, and forestry processes

Figure 6 displays the P-Graph diagram of integrated processes that combine the technological routes of the agricultural, livestock, and forestry industries in the province of Pastaza. This strategic integration aims to leverage the raw materials and waste products generated by these activities for the production of a variety of value-added by-products. Through filtration, dilution, sterilization, and fermentation, both sugarcane juice and whey can be transformed into citric acid, highlighting the potential synergy between the agro-industrial and livestock industries. Moreover, sugarcane bagasse and wood from the forestry sector, after being debarked, chipped, cooked, bleached, and dried, can be turned into kraft pulp, a key input for the paper industry.

In addition to its application in the design of technological routes and processes, P-Graph has demonstrated its potential in various industrial and management fields. According to [63], its ability to model nonlinear systems through artificial neural networks expands its applicability in complex logistical systems, enhancing strategic and operational decision-making. Meanwhile, [64] found that the use of P-Graph in efficient workflow management enables a more precise modeling of administrative and production processes, increasing efficiency and reducing redundancy in systems. This demonstrates the versatility of the methodology in terms of adapting it to various production environments.

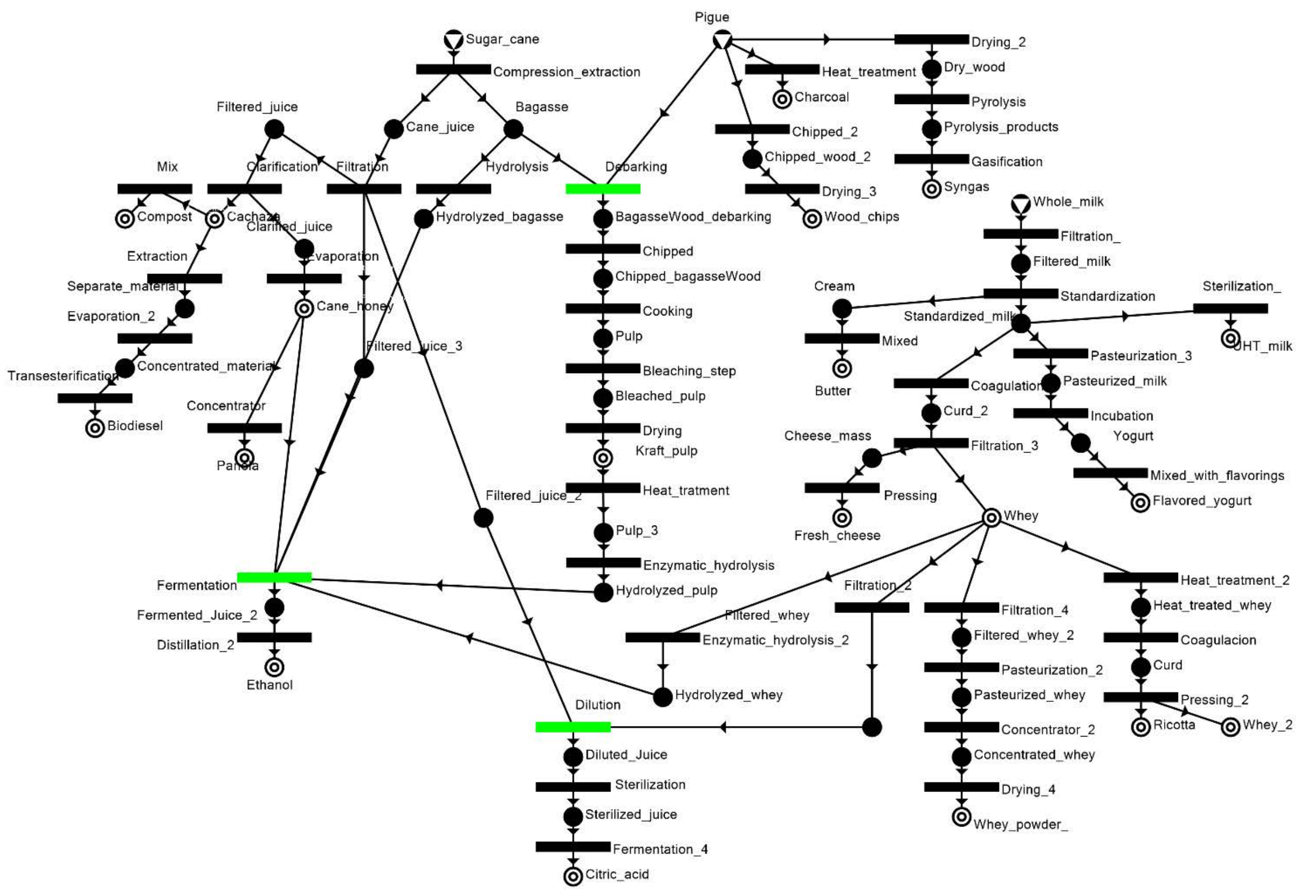


Figure 6 P-Graph of agricultural, livestock, and forestry routes

The integration of agricultural, livestock, and forestry technologies in Figure 6 shows the convergence of the unit stages of fermentation and distillation. Here, cane honey, concentrated sugarcane juice, bagasse, kraft pulp, and hydrolyzed whey can produce ethanol. This transformation process maximizes efficiency in waste management and demonstrates the viability of ethanol as a biofuel, whose global production stands at 74 billion liters [65]. Furthermore, the consumption of ethanol for producing biofuel is experiencing increases in demand due to historically high oil prices [66].

P-Graph, as described by [67], is particularly useful for systems that require adaptability and optimization in response to temporal variations and fluctuations in inputs, as demonstrated in Figure 6. This figure shows how ethanol, a high-value product, can be extracted from three different routes: agricultural, livestock, and forestry. The ability to adapt to seasonal cycles and the variable supply of raw materials, such as sugarcane juice, whey, and biomass, are crucial aspects in optimizing ethanol production.

The study by [68] focused on the production of biomass-based energy using flexible inputs through P-Graph, a key concept when dealing with resources that have variable properties and availabilities, as is the case for biomass. As seen in Figure 6, this flexibility is crucial because inputs like cane honey, sugarcane juice, and hydrolyzed whey can vary in their composition and volume. The ability to use flexible inputs to model fermenters, as in ethanol production, would significantly increase the profitability of the integrated system in Pastaza by allowing greater adaptability and efficiency in converting these variable inputs into value-added products.

Risk analysis and redundancy are important aspects of any production system, including the one integrated in Figure 6. Redundancy can be a strategy to manage uncertainty and risks associated with variability in production and the supply of raw materials [69]. Therefore, applying a multi-objective risk analysis based on P-Graph helps to identify and mitigate potential points of failure or inefficiencies, ensuring the robustness and resilience of the system against fluctuations in agricultural, livestock, and forestry processing routes.

3.3.5 Barriers to implementation

The implementation of integrated technological routes presents barriers that require technical analysis to ensure their feasibility. Among the main challenges are the initial investment in infrastructure, equipment, and the scalability of technologies, which may limit their adoption in small-scale production systems. Additionally, the need for technical training is a constraint, given how the efficient execution of processes such as fermentation, distillation, and biofuel production requires specialized knowledge. Furthermore, the introduction of innovative products, such as whey-derived biofertilizers or biomass pellets, could face market resistance. Therefore, promotion and awareness strategies are necessary to highlight their environmental and economic benefits.
Market acceptance will depend on the differentiation of products in terms of sustainability, efficiency, and quality. The lack of commercial validation and environmental certifications could limit their entry into specialized markets, requiring the execution of pilot tests and the optimization of production processes. Moreover, the development of marketing strategies that showcase the competitive advantages of these products, along with training programs, is essential in order to ensure their proper implementation. Considering these barriers in future research will enable the establishment of effective strategies to enhance the sustainability and feasibility of the proposed technologies in the province of Pastaza.

4 Conclusions

Eleven technologies were identified for agricultural production, including the conversion of sugarcane into juice, cane honey, panela, ethanol, biodiesel, and kraft pulp. For the livestock sector, nine technologies were analyzed, such as the production of UHT milk, cheese, yogurt, milk candy, butter, ricotta, powdered whey, ethanol, and citric acid from whey. In the forestry sector, five technologies were highlighted for the utilization of species such as pigüe, including the production of pellets, charcoal, synthesis gases, kraft pulp, and ethanol.
The study contributes scientifically by providing an approach for the development of technological routes based on the relationship between raw materials, technology, and production in a specific region. This facilitates the valorization of local resources and the selection of technologies by considering sustainability and economic feasibility criteria. However, limitations associated with implementation are recognized, such as the need for adequate infrastructure, initial investment, and market acceptance. Therefore, it is recommended that future research focus on the experimental validation of the proposed technologies, cost analysis in real scenarios, and the evaluation of the social and environmental impact of their application. This will help confirm the effectiveness and sustainability of the proposed technological routes, providing a solid foundation for their implementation in the region.

5 Declaration of competing interest

We declare that we have no significant competing interests, including financial or non-financial, professional, or personal interests, that interfere with the full and objective presentation of the work described in this manuscript.

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7 Contributions

R. D. Vinocunga-Pillajo: Co-wrote the paper and performed the analysis. A. S. Romero-Vistín: Performed the analysis. F. M. Jiménez-Tamayo: Co-wrote the paper. C. A. Sánchez-Vallejo: Collected the data. E. Guardado-Yordi: Conceived and designed the analysis. A. Pérez-Martínez: Conceived and designed the analysis.

7 Data availability statement

The source of the data is specified in the methodology, and the access links are found in the bibliography.

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