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Coffee Waste Management Using Valorization Technology: Potential Development of Eco-Industrial Park in Jember Regency, Indonesia

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Abstract

In Indonesia, the coffee agroindustry is making a significant economic contribution, with some environmental issues, including water pollution, eutrophication, and greenhouse gas emissions. This agroindustry generates vast by-products, offering a potential opportunity for material and energy recovery through eco-industrial parks. Therefore, this study aimed to analyze coffee waste management through valorization technology and the potential development of a coffee-based eco-industrial park. A system engineering approach was employed using a case study of the coffee agroindustry in Jember Regency, Indonesia. The result showed suboptimal utilization of technological valorization, as only 15% - 20% of the total solid waste was effectively valorized, resulting in low economic added-value of the products produced. This condition was caused by several factors, such as insufficient knowledge about valorization technology, inadequate availability of technological equipment, and the absence of a well-established market share of added-value products from coffee waste. Furthermore, the coffee-based eco-industrial park (EIP) design identified three main functionalities and its environmental operating systems. The coffee-based EIP could be potentially improved through public-private partnerships and broadening the scope of valorized coffee waste, including spent coffee grounds and wastewater.

Keywords: Circular economy; Coffee agroindustry; Eco-industrial park (EIP); Sustainability; System engineering; Waste valorization

1. Introduction

Coffee is one of the most consumed beverages worldwide, with a projected market of USD 102,279 by 2023 (International Coffee Organization, 2022). In Indonesia, the coffee agroindustry plays a significant economic role as the primary producer worldwide. This commodity was the third largest plantation after oil palm and rubber in 2021, contributing 16.15% to plantation GDP and providing a livelihood for 7.8 million Indonesian farmers (BPS Indonesia, 2022). Despite the high economic contribution, the coffee agroindustry also raises environmental issues along its supply chain, including deforestation, water pollution, and greenhouse gas emissions (Laili *et al.,* 2022). Processing the cherry requires approximately 15 - 20 liters of water to produce 1 kg of coffee beans (Dadi *et al.,* 2018). This process generates wastewater containing mucus and fermentation residual (Woldesenbet *et al.,* 2014), characterized by corrosive and high acidity (Sahana *et al.,* 2018). The wastewater also contains toxic materials, namely tannins, phenolics, and alkaloids, inhibiting biological degradation, as well as COD of 3,100-14,343 mg/L and a BOD of 5,000 - 35,000 mg/L, resulting in water pollution (Ijanu *et al.,* 2020). Similarly, solid waste such as pulp, husk, silver skin, and residues generated from using fertilizers and herbicides (Chala *et al.,* 2018) contribute to soil pollution and eutrophication (Woldesenbet *et al.,* 2016). These wastes lead to the emission of greenhouse gas (GHG), air pollution due to energy use in production and transportation processes (Ribeiro *et al.,* 2018), as well as carbon emissions and accumulated impacts on human health (Giraldi-Diaz *et al.,* 2018).

The circular economy (CE) is a perspective where economic development is carried out harmoniously with consideration for resource depletion and environmental degradation (Illankoon and Vithanage, 2023). Based on the circle metaphor, CE shifts the traditional linear "take-make-dispose" model into a sustainable system by prioritizing the preservation and reuse of resources (Genovese and Pansera, 2021). This economic model aims to eliminate waste and promote the continual use of resources (Mulrow *et al.,* 2017). The essential principles of CE include the design for circularity and resource looping through closed-loop systems, waste minimization by promoting sustainable production and consumption practices and regenerating natural systems to enhance sustainability (Borello *et al.,* 2023). At the industrial level, an eco-industrial park (EIP) is associated with the concepts of CE. The EIP is an industrial complex designed to optimize resource usage and minimize environmental impacts through the symbiotic exchange of materials, energy, and water among co-located businesses (Fouladi et al., 2021). In the EIP, the principles of industrial symbiosis drive the establishment of a circular exchange network, thereby increasing resource efficiency and environmental benefits through a significant reduction in environmental impacts (Park and Ren, 2019). A previous study established that there is a strong relationship between the CE principles and the development of eco-industrial parks (Martin and Harris, 2018). By adopting the circular economy principles, EIP can reduce industrial environmental impacts through circular design, supporting the transition to a more sustainable and resilient economy (Liubarska *et al.,* 2018). An EIP minimizes by-products, energy, and wastewater from a production process through reuse and recycling within a complex industrial network. This approach aligns with the goals of a circular economy (Genc *et al.,* 2020) by facilitating the exchange of by-products, co-generate energy, and sharing infrastructure, leading to cost savings and resource conservation (Mousque *et al.,* 2020).

In Indonesia, the government implements policies and regulations that support the achievement of the Sustainable Development Goals (SDGs). This is included in Presidential Regulation No. 9 of 2017 on the National Sustainable Development Goals, which outlines the vision and targets of the country for 2030. The adoption of a CE model through the development of EIP has the potential to significantly contribute to achieving several of the United Nations SDGs (Belaud *et al.,* 2019). Developing an EIP can also stimulate economic growth, improve supply chain performance, grow new industries, and create fresh job opportunities (Massard *et al.,* 2018). Moreover, the Indonesian coffee agroindustry shows potential for EIP integration due to the characteristics of coffee solid waste, which can be harnessed as biomass and converted into economic value-added products using waste valorization technology (Araujo *et al.,* 2022). Waste valorization is a process of transforming waste materials or by-products into valuable resources, products, or energy using innovative processes and technologies (Ghinea *et al.,* 2020). In this study, the coffee valorization technology used encompasses several processes such as fermentation, extraction, biorefinery, and metabolic molecular engineering. These processes facilitate the transformation of husk, pulp, spent ground coffee, and wastewater into various value-added products (Kovalcik *et al.,* 2018), including compost, animal feed, organic fertilizer, biogas, bioethanol, and cascara (Desai *et al.,* 2020).

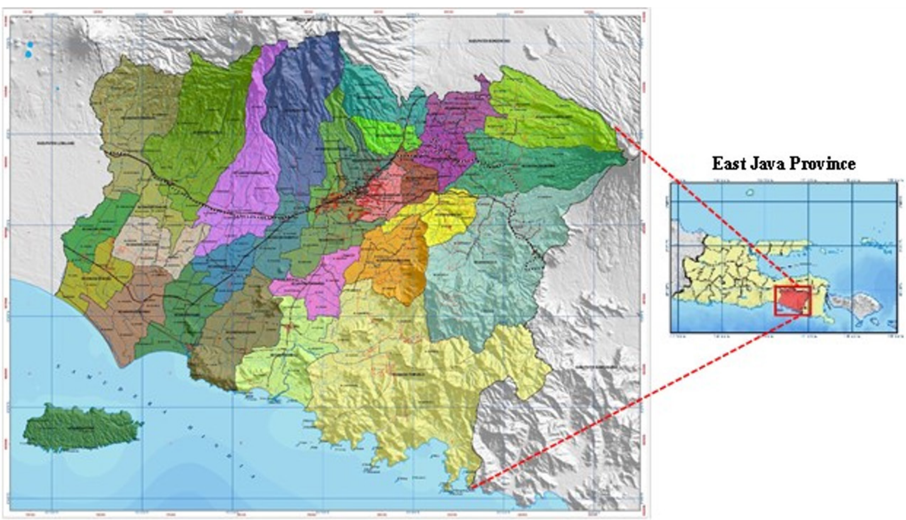
Previous studies show rapid developments in valorization technology, including torrefaction, biorefinery, transesterification, extrusion, and nanotechnology, which have transformed coffee by-products into vary widely products with high economic value.

This approach has been scientifically proven to transform coffee by-products into bioethanol (Lee *et al.,* 2023), mulching film (Pagliarini *et al.,* 2023), biodiesel (Bekele *et al.,* 2022), food packaging (Terroba-Delicado *et al.,* 2022) and silver nanoparticles (El-Desouky *et al.,* 2022). In the coffee waste valorization industry, creating a sustainable business model requires a social and economic perspective, including technical considerations. Within this framework, this study identified gaps in the social and economic perspectives for the implementation phase of coffee waste valorization. Although existing literature has explored EIP development in developed countries through a quantitative approach using a mathematical model (Genc *et al.,* 2020; Kuznetsova and Zio, 2016; Mousque *et al.,* 2020; Theo *et al.,* 2016; Shah *et al.,* 2020). There is still a lack of information on EIP development in developing countries, particularly in coffee agroindustry. Therefore, this study aimed to analyze coffee waste management through valorization technology and the potential development of EIP. A system engineering method was used to design the EIP using perspectives of a complex system. The location used was the coffee agroindustry in Jember Regency, East Java, the fifth-largest coffee-producing region in Indonesia. The investigation effectively addressed the gaps in the literature by analyzing the coffee waste valorization, encompassing technical, social, economic, and environmental aspects. Furthermore, it served to enhance EIP advancement in developing countries as a recommendation for a regional development policy centered around sustainable coffee agroindustry in Jember Regency.

2. Methodology

2.1 Study Area

The case study is located in Jember Regency, East Java, which ranks as the fifth-largest coffee-producing region in Indonesia. Geographically, Jember Regency was located at 7059'6" to 8033'56" South Latitude and 113016'28" to 114003'42" East Longitude. The territory covers an area of 3,293.34 km2, with a topographical character of fertile canyon plains in the central and southern parts, surrounded by mountains along the western and eastern boundaries. The elevation of this regency ranges from 0 to 3,300 meters above sea level (masl), with the majority of the area (37.75%) at an altitude of 100 to 500 masl, 17.95% at 0 to 25 masl, 20.70% at 25 to 100 masl, 15.80% at 500 to 1,000 masl, and 7.80% at over 1,000 masl. The southwest region has plains at 0 – 25 masl, while the northeastern region bordering Bondowoso and the southeastern bordering Banyuwangi have altitudes above 1,000 masl. Figure 1 shows the administrative map of the Jember Regency.



Source: https://jemberkab.go.id (accessed May 22nd, 2023)

Figure 1. Administrative map of Jember Regency, East Java Province

2.2 Data Collection

This study employed a qualitative approach with a single case study of Jember Regency coffee agroindustry. The secondary and primary data used were collected from April 2022 to January 2023 at the location. The primary data included the current condition of the coffee supply chain and situational analysis of the Jember coffee agroindustry, which were collected through field observations and in-depth interviews with key actors in the agroindustry. The snowballing technique was employed to gather initial information about key actors. Subsequently, in-depth interviews were conducted to obtain primary data related to EIP potential development in Jember, with details of informants and the number of interviewees, as shown in Table 1. A series of in-depth interviews with informants were conducted using open-ended questions regarding the coffee agroindustry, in this case, study with topics including (1) existing conditions and developments in the last 5 years of the coffee supply chain and its actors, (2) production procedures business processes model, product transformation, and value addition in coffee agroindustry, (3) the condition of sustainability pillars, namely technological, social, and economic aspects of the agroindustry, (4) potential and existing valorization of coffee waste, (5) existing and required policies as well as regulations related to the agroindustry. The same open-ended questions were delivered to informants to ensure various perspectives, considering validation and triangulation of in-depth interview data.

In this study, secondary data were collected through a literature review to obtain information related to eco-industrial development, including potential byproduct/waste generation and exchange, socio-economic conditions, natural resources, technology characteristics, coffee environmental impact report, and relevant regulation and policy. These data were collected from reports of coffee farmers, processors, cooperatives, Jember Regency government, statistical data related to the coffee agroindustry, previous studies, and other relevant documentation. Furthermore, an interview was conducted with nine management personnel of coffee processor firms and one staff of the Jember local government to verify the collected data and acquire supplementary backgrounds on EIP development.

2.3 Analytical Framework: System Engineering Approach

System engineering is the multi-disciplined application of analytical, mathematical, and scientific principles for formulating, selecting, developing, and maturing an optimal solution from a set of viable candidates that has acceptable risk, satisfies user operational needs, minimizes development as well as life cycle costs, and balances stakeholder interests (Wasson, 2015). In this context, EIP is a highly complex system involving the interaction and transfer of material, energy, and water between firms within the system (Devanand *et al.,* 2020). Analytically, an EIP system

Table 1. Informants of in-depth interviews

Actors	Number of interviewees
Coffee farmer	16 informants
Coffee farmer group	4 groups
Coffee processor	9 firms
Cooperation	1 cooperation
SME of coffee waste processor	2 SMEs
Coffee researcher of Jember University	5 informants
Researchers of the Coffee and Cocoa Research Center	3 informants
Department of Food Crops, Horticulture, and Plantation	2 informants

is represented as a simple entity comprising inputs–transfer functions to produce outputs such as products or services. In this study, the behavioral patterns were analyzed to describe the interaction of the EIP system with its operating environment, including stakeholders, roles, missions, objectives, resources, internal controls/ constraints, opportunities, threats, and operating constraints. Moreover, this system should efficiently and effectively add value to its inputs through the transfer function to produce desirable outputs.

This study used the System of Interest (SOI) analytical framework in Figure 2, which depicted the coffee-based EIP system construct. As a system engineering method, the SOI framework has been proven to be an effective method for designing EIP. Generally, EIP is a complex and integrated system that involves the collaboration of various industries, stakeholders, and processes to achieve resource efficiency, waste reduction, as well as environmental sustainability. Compared to the quantitative mathematical models commonly used in the designing process, the SOI framework provides a structured and holistic approach to designing, optimizing, and managing this intricate system.

3. Results and Discussion

3.1 Design of Coffee-based EIP: System Entity Construct

Coffee is the main plantation commodity in the Jember Regency area, alongside oil palm, coconut, rubber, cocoa, sugarcane, tea, and tobacco. This regency experienced a significant decrease in coffee plantation area from 14,586.5 ha in 2021 to 6.442,45 ha, covering 16 sub-districts in 2022. Moreover, in 2022, Jember produced 4,193.53 and 353,326 tons of coffee from estate crop plantation areas and forest product production, respectively (BPS Jember, 2020). The agricultural sector employs 483,947 workers, representing 18.4% of the total population. Among the 16 sub-districts involved in coffee production, Silo emerged as the largest coffee producer in Jember.

In this study, the wet processing method was used to produce coffee beans for both Robusta and Arabica coffee. This involved a fermentation process that produced high-quality coffee beans compared to the dry processing method. The processing technologies used were pulper, fermentation, washing, and coffee bean sorting machines. Based on the output, for every 1 kg of coffee cherry processing, approximately 35% was converted to coffee beans or derivative products, while 65% constituted solid waste. As shown in Figure 3, data showed that only 15% of the coffee solid waste, such as pulp and husk, was valorized into animal feed, and the remaining 85% was directly disposed of into the environment.

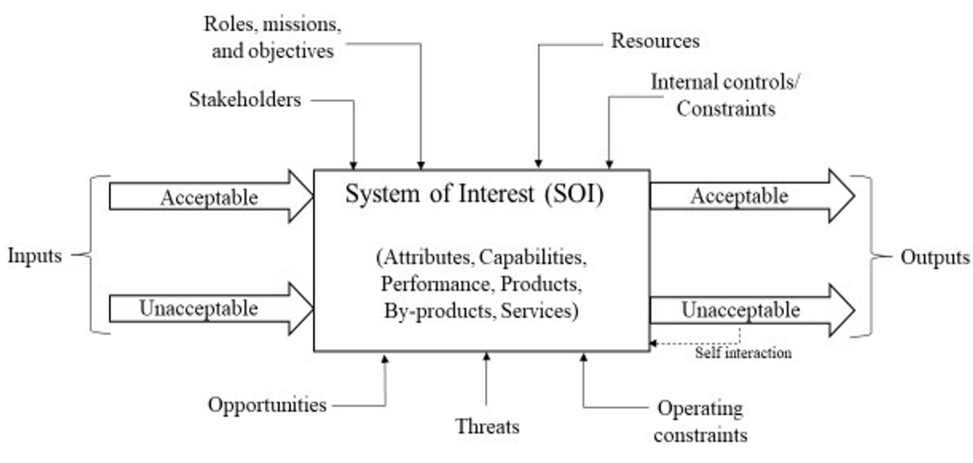


Figure 2. Analytical system entity construct

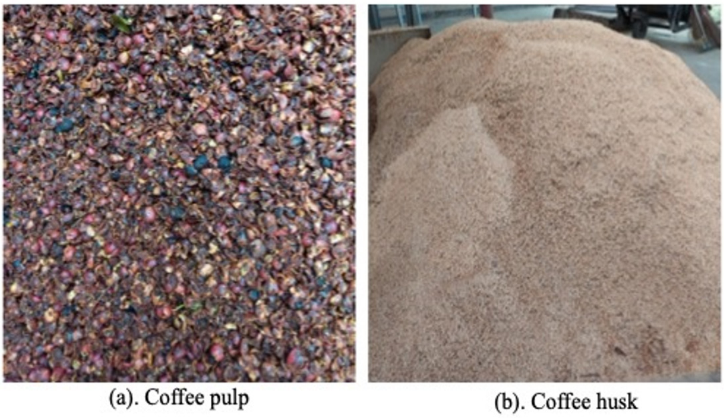


Figure 3. Coffee solid waste in the case study

Based on the analytical system entity construct, the design of coffee-based EIP in this case study focused on production activities in the supply chain, as shown in Figure 4. The EIP design involved supply chain actors, namely farmers, processors, collectors, and SMEs as by-product processors. In the EIP design, the three main functions that were effectively carried out included coffee processing to produce beans and derived products, solid waste and wastewater processing to obtain added-value products, as well as interactions and material exchange within EIP. These functions referred to the transformational processing during coffee production and by-products within EIP. Moreover, the EIP functionality was evaluated based on the extent to which the transformation process turned the input into an acceptable output. When the EIP functionality did not work properly, the output produced failed to meet system requirements. In Figure 4, the acceptable output was coffee beans, coffee-derived products, and value-added items such as compost/fertilizer, animal feed, cascara, and biogas. In contrast, the unacceptable output was in the form of unprocessed coffee solid waste and wastewater, indicating that EIP was not functioning effectively and efficiently. The performance of the coffee-based EIP functionality was also determined by the input of the system, where the acceptable inputs were coffee cherries, solid waste, wastewater, water, energy, technology, and knowledge. Meanwhile, the unacceptable inputs were low-quality coffee cherries and a lack of technology.

The coffee-based EIP design operated and interacted in the system environment, which consisted of stakeholders, roles, mission, objectives, resources, internal controls, opportunities, threats, and operating constraints. This study defined the mission as minimizing environmental impacts, optimizing the coffee value chain, and increasing coffee agroindustry sustainability. The stakeholders were coffee farmers, processors, SMEs, and managers who directly interacted with EIP to operate the system functionality. Meanwhile, collectors, financial institutions, and coffee exporters indirectly interacted with EIP due to their relationship with the performance functionality.

Resources were identified as a crucial part of the system operating environment of the coffee-based EIP. The production plant is the primary resource facilitating the main processes and functions, as well as infrastructure, logistics, and transportation both within and from the EIP to the Jember coffee agroindustry supply chain. In this case study, other resources were financial support from cooperatives, banks, and investors. SOP of coffee processing and product quality control (QC) as internal control mechanisms in EIP was also required to ensure EIP functioned effectively and efficiently. The functionality was also influenced by external factors at a higher level in the form of opportunities and threats. Opportunities were external aspects that were not regulated, but when appropriately responded to, these factors positively impacted the performance of coffee-based EIP in Jember. Moreover, opportunities included increased coffee demand, the market opportunity for coffee waste-based products, and technological support.

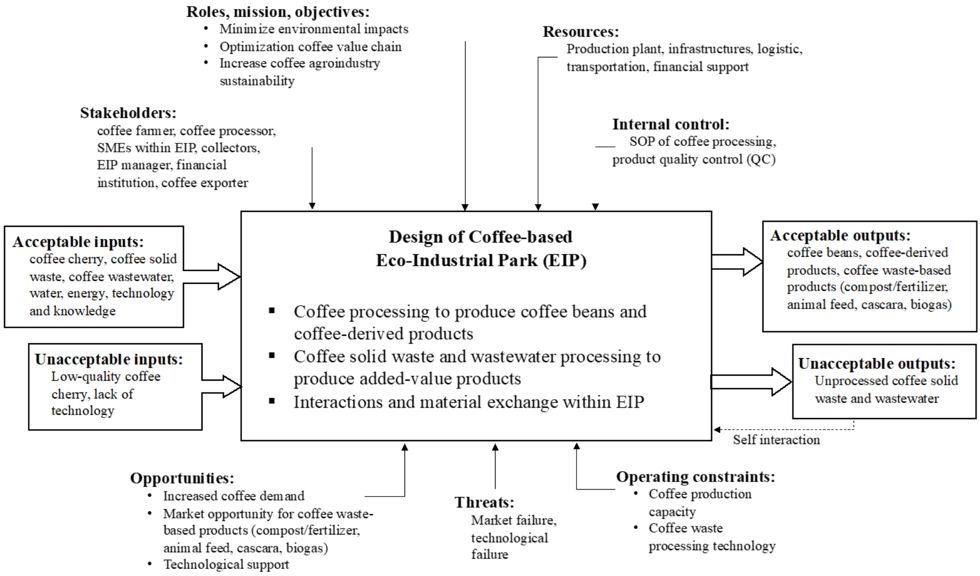


Figure 4. System entity construct of coffee-based EIP

3.2 Coffee Waste Valorization Technology in EIP

Waste valorization is an alternative approach to solving environmental pollution caused by solid waste generated during industrial production, including in coffee agro-industry cases (Capanoglu *et al.,* 2022). Generally, coffee solid waste such as pulp and husk is generated during the cherry processing into beans, while spent coffee grounds are produced post-consumption (Lestari *et al.,* 2022). Coffee processing using wet or dry methods produces large amounts of solid waste, exceeding 10 million tons annually (Echeverria and Nuti, 2017). This waste constitutes biomass containing useful compounds that are influenced by processing method, waste type, and species variety. These factors determine the chemical compounds in coffee solid waste (Blinova and Sirotiak, 2019). Coffee by-products, such as pulp, husk, silver skin, and spent coffee grounds, are promising raw materials for various industries (Nguyen *et al.,* 2019). Through the application of appropriate valorization technology, coffee waste can be transformed into a range of valuable products including bio-sugar, biofuel, fertilizer, enzymes, dietary fiber, and bioactive compounds (Durán-Aranguren *et al.,* 2021).

Coffee solid waste constituted a high proportion of the coffee cherry biomass in dry and wet processing methods, reaching 50% pulp and 20% husk, respectively (Arya *et al.,* 2022). In this study, solid waste of approximately 60% to 75% of the input coffee cherries was generated for every ton processed. Using the wet processing method, the dominant waste generated was pulp and husk, which was the focus of the valorization technology. In 2022, the total production of coffee cherries in the Jember Regency was 4.548,856 tons, resulting in 2.501,87 tons of pulp and 909,77 tons of husk. Presently, coffee waste management in this case study showed that only 15% of pulp and husk were processed, while the remaining 85% were unprocessed solid waste directly disposed to the landfill. This phenomenon resulted in soil and water contamination, the production of methane and greenhouse gases, as well as land occupation. The existing coffee waste management indicated the traditional linear economy (take-make-dispose) model, which was still dominant, contrary to the CE concept. In a CE, coffee waste is a valuable resource, where disposing of a significant amount to landfills negates the opportunity for resource loop closure and potential economic revenues. Based on the EIP principles, the current coffee waste management indicated a lack of industrial symbiosis in the case study area. The low level of valorization, accounting for 15% of the total coffee waste, showed minimal collaboration between the agroindustry and other potential sectors capable of using the waste as resources. The case study also identified the main obstacles to effective management, including the limited capability of valorization technology, inadequate waste handling capacity, the lack of robust business processes between actors in the agroindustry, and the absence of a market for valorized products.

Previous studies have shown various added-value products from valorizing coffee pulp and husk. Based on their usage, these value-added products can be categorized into several groups, including alternative energy sources, such as biogas, bioethanol, and hydrogen (Villa Montoya *et al.,* 2020). These also included cellulase, lignocellulose, and xylanase enzyme production, as well as bioactive compounds, such as chlorogenic acid, caffeic acid, and lactic acid (Magoni et al., 2018), food (Prihadi *et al.,* 2020), animal feed (Didanna, 2014), and fertilizer (Sayara *et al.,* 2020). The existing coffee waste valorization showed that pulp and husk were the solid waste type being valorized, characterized by high moisture and contents of chemical compounds, with the potential as raw material for several thermochemical conversions, particularly energy production (Martinez *et al.,* 2021). However, the valorization of coffee pulp and husk in this study was limited to producing biogas, fertilizers, animal feed, and cascara beverages, as shown in Table 3.

The valorization technology used in this study was relatively simple, involving unregulated activities carried out by cooperatives, UKM, and farmer groups. Generally, the valorization of coffee waste is only carried out during the main harvest when coffee pulp and husk are available in abundance. Biogas is also produced communally in farmer groups through digestion technology in pulp and husk by mixing other components in a bioreactor. This biogas substitutes some of the household energy needs of coffee farmers, limiting its application for commercial sale. Similarly, fertilizer is produced using relatively simple composting technology by individual farmers and groups. Organic fertilizer is usually packaged in sacks, with limited marketing coverage to coffee farmers in the Jember Regency. Animal feed was produced by mixing the fermented coffee pulp with several components at a maximum proportion, ranging from 10% to 30%, but with limited

Table 2. The Chemical Compounds in Coffee Waste Based on Previous Studies

Chemical Compounds	Coffee pulp	Coffee husk	Spent coffee grounds
Carbohydrates	44.0 - 55.0	57.8	60.3 - 82.0
Cellulose	9.18 - 63.0	39.0 - 61.0	8.6 - 47.3
Hemicellulose	2.0 - 66.0	4.0 - 10.0	32.0 - 43.0
Xylose	-	-	0.3 - 1.1
Arabinose	-	-	1.7 - 3.6
Mannose	-	-	19.1 - 21.6
Galactose	-	-	8.2 - 16.4
Rhamnose	-	-	0.1
Lignin	12.2 - 22	9.0	23.9 - 33.6
Lipids	0.3 - 2.5	0.5 - 6.0	6.0 - 38.6
Proteins	4.4 - 12.0	3.0 - 13.0	11.5 - 18.0
Ash	5.4 - 15.4	6.0	1.1 - 2.2
Caffeine	0.8 - 5.7	0.5 - 2.0	0.02 - 0.4
Tannins	1.8 - 8.6	4.5 - 9.3	0.02
Chlorogenic Acids	1.0 - 10.7	2.0 - 12.6	1.8 - 11.5
Pectins	4.4 - 12.4	0.5 - 3.0	0.01

Source: (Nguyen *et al.,* 2019; dos Santos *et al*., 2021).

Table 3. Mapping of added-value products in the Jember Coffee Agroindustry

Source	Added-value products	Valorization technology	In Case study
Coffee pulp	Biogas	Co-digestion	Utilized
	Bioethanol	Saccharification and fermentation	-
	Cellulase enzymes	SSF *Acinetobacter sp.*	-
	Lignocellulase enzymes	SSF *Bacillus substilis* CCMA 0087	-
	Chlorogenic acid	SSF *Rhizomucor pusillus,* and *Trametes sp.*	-
	Caffeic acid	SSF *Trametes sp.*	-
	Lactic acid	Fermentation *Bacillus coagulans*	-
	Cascara beverage	Drying	Utilized
	Animal feed	Mixing	Utilized
	Fertilizer	Vermicomposting	Utilized
Coffee husk	Biogas	Co-digestion	Utilized
	Bioethanol	Saccharification and fermentation	-
	Hydrogen	Bioprocess-microbial consortium	-
	Enzyme xylanase	SSF using *Penicillium sp.*	-
	Activated carbon powder	Chemical activation	-
	Dietary fiber supplement	Extrusion process	-
	Colorant	Extraction	-
	Mushroom cultivation	Fermentation	-

application. Furthermore, cascara beverages are produced by several SMEs with a simple drying and packaging process. Although these products have been sold commercially in Jember and its surroundings, their market acceptability is limited due to relatively low consumption compared to coffee, tea, or chocolate.

3.3 EIP in Promoting Sustainability and Circular Economy

The use of valorization technology to recover added-value products has been shown to significantly enhance economic value and increase industry profit (Rosello-Soto *et al.,* 2015). In the coffee agroindustry, the selection of the appropriate waste valorization technology will economically affect the optimization of the added-value products (Errico *et al.,* 2023), necessitating the proper management of the selected method (Gavahian *et al.,* 2018). Therefore, this study identified the factors causing the non-optimal condition of the coffee waste valorization in the Jember coffee agroindustry. The first factor was the lack of valorization technology owned by SMEs engaged in producing added-value products, as shown in the insufficient knowledge regarding valorization and available technological equipment. The existing added-value products in the case study exhibited relatively low technological content and limited economic value in biogas, cascara beverages, fertilizer, and animal feed, thereby increasing the need for optimization, which was influenced by the technology capability of the coffee waste processing firm (Sengupta *et al.,* 2020). This phenomenon also produced added-value products such as enzymes and bioactive compounds, with quality that fulfilled the standards and efficient production costs (Anastasia and Paraskevi, 2019). The selection of excellent technology valorization also allows firms to obtain added-value products with the best characteristics and quality (Massaya *et al.,* 2019).

The second factor is that the market share for added-value products from coffee waste has not been established. During the selection process, the availability of market share and price guarantee for valorized products are crucial (Ghisellini *et al.,* 2016). In this study, products such as biogas, fertilizers, animal feed, and cascara beverages have not been widely commercialized due to the inability to obtain permits for their commercial sale. The reluctance of SMEs to apply for commercial marketing permits for fertilizer and animal feed is due to perceived limited market share, which may result in minimal profit. The introduction of added-value products also demands careful consideration for the co co-evolution of new markets and social practices (Pongkijvorasin and McGreevy, 2021).

The EIP design plays a crucial role in optimizing valorization technology with a high degree of certainty (Tulchynska *et al.,* 2023). In this study, the initial phases of further coffee-based EIP development have been mapped out, including the identification of important functions and potential main actors in EIP. Meanwhile, the abundant coffee waste, constituting approximately 60% to 75% of the total coffee cherry, significantly increases the potential for developing coffee-based EIP, considering the ability to exchange materials and energy (Hammam *et al.,* 2023). The high economic value is also crucial for optimizing the valorization function in the development of coffee-based EIP (Zhao *et al.,* 2022; Boix *et al.,* 2023), and the selection of sustainable options (Rivera *et al.,* 2020). For example, the valorization of coffee pulp to produce cellulase enzymes enables higher economic value compared to the production of fertilizer. Consequently, investment in solid-state fermentation (SSF) technology with Acinetobacter sp. emerges as a viable strategy for cellulase enzyme firms. Increasing the added value to the valorization of coffee waste impacts the socioeconomic benefits of EIP, potentially enhancing the environmental sustainability of the coffee agroindustry up to the realization of a CE (Gebreeyessus, 2022).

The EIP development necessitates the role of a manager, as it is generally carried out top-down (Butturi *et al.,* 2020). The coffee-based EIP in Jember has the potential to develop through a public-private partnership, which can attract investment. This partnership scheme enables interactions and order of stakeholders embedded in the EIP, particularly in the early development stages (Dai *et al.,* 2022). Furthermore, the coffee-based EIP development requires broadening the valorization scope, including spent coffee grounds and wastewater, which have high added value (Lee *et al.,* 2023). This development is carried out by establishing a new company as the executor of coffee waste valorization or attracting external companies to join the EIP (Farooque *et al.,* 2022). However, merging companies into EIP does not require physical relocation in Jember. This aligns with the EIP concept developed in the literature, where "co-located" extends beyond a physical location to encompass the same region or province (Winans *et al.,* 2017).

The development of coffee-based EIP significantly increased the sustainability of the Jember coffee agroindustry. From an environmental perspective, it potentially reduces environmental impacts and minimizes the use of raw materials from coffee solid waste substitutions. Economically, it potentially reduces the cost of coffee production, creates new jobs, increases the added value to the coffee value chain, stimulates the growth of new companies, attracts investment, and improves the welfare of the people around the coffee-based EIP. Based on the social aspect, EIP creates consumption of environmentally friendly products, reduces risk potential in human health, upgrades society with special knowledge, and improves company image. These results indicated that the implementation of valorization technology in coffee-based EIP potentially enables the conversion of the linear economy into a circular economy (Serna-Jimenez *et al.,* 2022).

The overarching framework of the Circular Economy (CE) aimed to create a closed-loop system where waste is minimized and resources are continually repurposed, reused, and recycled. In contrast to the traditional linear economic model, the CE paradigm emphasizes the importance of resource efficiency and longevity. In this study, only a fraction of coffee waste was valorized, indicating a divergence from the foundational tenets of CE. Although the industry had taken steps to valorize certain by-products, the potential to create a more comprehensive loop, where almost all waste was converted to value, remained largely untapped. This discrepancy highlighted missed opportunities to advance toward a truly circular model that required bridging. Eco-Industrial Parks (EIP) epitomized the principle of industrial symbiosis and were designed to foster collaboration between businesses. This ensured the conversion of waste to another resource, thereby promoting mutual benefits and reduced environmental footprint. The coffee-based EIP design in this study emphasized that coffee processing and waste valorization aligned with the core principles of EIP. However, the noted challenges in the coffee agroindustry, such as the knowledge deficit and technological gaps, indicated potential barriers to realizing a fully functional EIP. These barriers would be mitigated in a mature EIP setting through shared knowledge, resources, and collaborative problem-solving.

4. Conclusion

In conclusion, this study showed that the existing valorization technology involved the use of coffee husk to produce biogas, while the coffee pulp was employed for biogas, fertilizer, animal feed, and cascara beverages. However, the application of valorization technology has not been optimally carried out, as only 15% - 20% of the total solid waste was valorized, leading to limited production of added-value products. This condition was caused by insufficient knowledge of valorization technology, limited technological equipment, and the absence of an established market share for added-value products from coffee waste. In this study, the coffee-based EIP design identified three main functionalities in the coffee-based EIP design. These included coffee processing to produce coffee beans and coffee-derived products, solid waste and wastewater processing to generate added-value products, as well as interactions and material exchange within EIP. Moreover, improving coffee-based EIP was potentially carried out through public-private partnerships to broaden the scope of valorized coffee waste, including spent coffee grounds and wastewater, which exhibited high added-value potential.

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