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Optimization of industrial symbiosis in coffee-based eco-industrial park design

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ABSTRACT

BACKGROUND AND OBJECTIVES: The coffee agroindustry in Indonesia plays a significant economic role as the third largest coffee producer worldwide. Despite the high economic contribution, the coffee agroindustry also raises environmental issues along its supply chain. Coffee solid waste constitutes biomass containing useful compounds promising as raw materials for added-value products through the implementation of industrial symbiosis. Eco-industrial parks create value through industrial symbiosis, emphasizing the principle of a closed-loop production system, simultaneously decreasing the use of raw materials and waste. This study aimed to analyze and develop a coffee-based eco-industrial park design via a systems engineering approach and optimization of industrial symbiosis in closed-loop coffee production.

METHODS: This study employed a case study in the Ketakasi coffee-producing center in Jember, Indonesia. Data collection was conducted through field observation and a series of in-depth interviews. The development of eco-industrial park design followed a systems engineering methodology, as demonstrated through the utilization of Business Process Model and Notation. Subsequently, the optimization of industrial symbiosis within eco-industrial parks was realized using a mixed-integer linear programming mathematical model.

FINDINGS: The eco-industrial park design presents the actors, internal business processes, material and data exchanges, various actors' interdependence and critical roles in material exchanges, and value creation processes using valorization within the eco-industrial park. The role of the Ketakasi cooperative as a facilitator of material exchange and manager of the eco-industrial park is pivotal. The utilization of data integration enhances the transparency and efficiency of information exchange among eco-industrial park participants, promoting predictability and reliability in material exchange. The application of the mixed-integer linear programming optimization model has provided a structured approach to maximizing the value creation within the eco-industrial park through the valorization of 72.3 percent of coffee pulp and 68.5 percent of spent coffee grounds into cellulase enzymes and ultraviolet shields.

CONCLUSION: This paper presents a structured framework for efficiently managing material exchange processes within an eco-industrial park, contributing to environmental sustainability and economic value creation. This study contributes to the knowledge gap in the literature by developing an inclusive eco-industrial park design that facilitates the optimization of the value creation process through valorization technology. This study also adds to sustainable agriculture management literature through a coffee-based eco-industrial park design.

NUMBER OF REFERENCES	NUMBER OF FIGURES	NUMBER OF TABLES
83	6	6

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INTRODUCTION

The extensive industrial growth driven by capital investment leads to significant natural resource consumption and environmental issues (Shen and Peng, 2020; Samimi *et al.,* 2023). Circular economy (CE) is an economic model striving to separate economic expansion from the exhaustion of resources and environmental decline (Farooque *et al.*, 2022). This model aims to shift the traditional linear "take–make–dispose" model with a restorative system emphasizing recycling waste materials and effectively recovering the waste value (Yu *et al.,* 2021). CE promotes maximum recycling regarding the increasing resource availability constraints to improve resource use efficiency and effectiveness, leading to resource conservation (Ghisellini *et al.*, 2018). A linear economy extracts resources, transforms them into products, uses them, and disposes them as waste. By contrast, CE promotes resource efficiency, sustainability, and the continuous use of materials in closed-loop systems (Bai *et al*., 2019). CE offers novel perspectives to industrial enterprises, aiming to enhance efficiency by reducing the consumption of materials and natural resources and promoting the reuse of products, materials, and by-products (Kirchherr *et al.*, 2017). One promising method to achieve CE is by establishing industrial symbiosis (IS), a concept inspired by natural ecosystems where different organisms work together for mutual advantage (Tumilar *et al.*, 2020). IS is defined as a concept in which traditionally separate entities collaborate for mutual competitive benefits, encompassing the physical sharing of materials, energy, water, and by-products (Neves *et al.*, 2020). The key principles of IS include efficient use of resources, waste reduction, and collaborative advantage, all contributing to economic, environmental, and social benefits (Stucki *et al.*, 2019). Adopting IS in industrial systems offers economic and environmental benefits, including enhanced profitability and competitiveness by reducing raw material and disposal costs, innovation and new revenue streams, collaborative networks, environmental regulation compliance, and decreased emissions and environmental pollution (Tolstykh *et al.*, 2023). IS encourages companies to shift from linear production to a circular model, prompting the re-evaluation and redesign of supply chains and considering new stakeholders, waste's impact on product development, economic investments, and technological resources (Demartini *et al.,* 2022). IS focuses on the concept of deriving values through waste sharing; in fact, what is regarded as waste by one company can serve as a resource for another (Lawal *et al.,* 2021). Substituting inputs with waste materials enables companies to boost their production efficiency, leading to cost savings by reducing waste disposal and input procurement expenses (Fraccascia and Yazan, 2018). The potential for reusing waste materials emerges through integrating industrial clusters to establish IS and effectively create closed-loop cycles of materials (Ormazabal *et al.*, 2018). An eco-industrial park (EIP) is described as an embodiment of the IS concept at the meso/industrial level (ElMassah, 2018), where distinct industrial entities come together and achieve a measure of IS (Belaud *et al.*, 2019). The concept of EIP promotes implementing an analogical model based on natural ecosystems to enhance resource utilization efficiency on a park scale, ultimately aiming for a sustainable industrial system regarding the social, economic, and environmental aspects of sustainability (Valenzuela-Venegas *et al*., 2016). EIP increases industrial system sustainability through the improvement of environmental performance, including great economic growth, diminished resource consumption, and decreased pollution and emission (Liu *et al.,* 2015). EIP has fostered beneficial connections between colocated firms, encouraging them to share natural and economic resources and enhancing sustainability and economic gains (Kastner *et al.*, 2015). EIP creates value through IS, emphasizing the principle of a closed-loop system within EIP and simultaneously decreasing the use of raw materials and waste (Winans *et al.*, 2017; Fan *et al.*, 2017). As a representative of closed-loop initiatives of IS conducted on a cluster scale, EIP promotes a cluster of proximate firms that collaboratively share specific resource and energy flows, thereby augmenting their combined energy and resource efficiency (Chen *et al.*, 2023). In practice, operations within an EIP experience daily fluctuations, leading to a continuous encounter with uncertainty (Liberona *et al.*, 2023). EIP performance is evaluated from how the closed-loop design functions effectively through IS optimization within EIP, including waste and by-product exchange optimization (Yu *et al.*, 2023). An efficient EIP design aims for maximum cyclicity, minimizing waste outflow and external resource procurement (Genc *et al.,* 2020). IS optimization is crucial to attain maximum cyclicity in the design of EIPs, in consideration of the involvement of diverse stakeholders and their respective interests. A systematic literature review was conducted to scrutinize the state of the art in IS optimization in EIP literature by using the Scopus database. Publication searches were carried out through the search engine in the Scopus database using the keywords "eco-industrial park" and "optimization," and 207 papers published from 2003 to 2023 were collected.

Based on the subject area, previous studies on IS optimization in EIP mostly focused on environmental science, engineering, and energy fields (Fig. 1). On the contrary, EIP optimization in the agriculture field, including agroindustry, is the least addressed with 1.3 percent (%) of total publication number. The 207 papers were reviewed through an iteration process, including the summarize, synthesize, compare, and criticize stages, resulting in 7 main papers that are state of the art in this research (Table 1).

The general method utilized in the optimization of IS in EIP identified from the literature review is a quantitative approach using mathematical models, namely, the mixed-integer linear programming (MILP) and the mixed-integer nonlinear programming (MINLP). Table 1 summarizes that optimization of IS within EIP was carried out using the MILP method to obtain the optimum solution for operating cost (Yu *et al.*, 2023), total cost of system (Ventura *et al.*, 2023), operational cost saving (Jing *et al.*, 2021), water consumption (Aussel *et al.*, 2023), energy exchange (Mousque *et al.*, 2020), and wastewater treatment cost (Hu *et al.*, 2020). The MINLP method was employed to obtain the optimum solution for energy exchange (Misrol *et al.*, 2022). In developing the MILP and MINLP optimization models, these studies focused on the objective function of EIP operational cost efficiency, as well as optimizing energy distribution and water consumption within EIP. Limitations in these studies were identified, resulting in knowledge gaps, including the lack of perspective

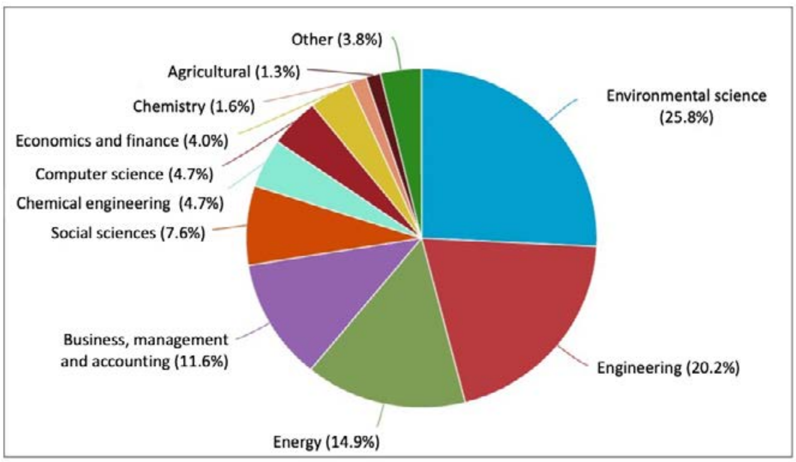

Fig. 1: Literature on IS optimization within EIP from 2003 to 2023 based on the subject area in the Scopus database

Table 1: State-of-the-art previous studies on IS optimization in EIP based on Scopus database

Optimization method	Objective function	Sources
Mixed-integer linear programming	Optimization of operating cost	Yu *et al.*, 2023
Mixed-integer linear programming	Optimization of the total cost of system	Ventura *et al.*, 2023
Mixed-integer linear programming	Optimization of water consumption	Aussel *et al.*, 2023
Mixed-integer nonlinear programming	Optimization of energy exchange	Misrol *et al.*, 2022
Mixed-integer linear programming	Optimization of operational cost saving	Jing *et al.*, 2021
Mixed-integer linear programming	Optimization of energy exchange	Mousque *et al.*, 2020
Mixed-integer linear programming	Optimization of wastewater treatment cost	Hu *et al.*, 2020

objective function on optimization for value creation in terms of waste valorization into added-value products and the lack of addressing the dynamics and interdependence of actors' interests within EIP, which influence their business process. EIP, as an industrial system, is composed of business entities primarily focused on conducting business operations, carrying out the value creation process, and creating economic profits. The process of value creation is an important function facilitated by EIP in parallel with the aim of minimizing environmental impacts. The implication is that optimizing the value creation process in EIP through technology valorization is urgent and important to fill the literature gap. The challenge of the value creation optimization in EIP is to build material exchanges that are economically mutually beneficial for all EIP participants (Afshari *et al.*, 2018). This study addresses this knowledge gap by developing an inclusive EIP design that facilitates the optimization of the value creation process through valorization technology. Optimization of the value creation process is carried out with the perspective of maximizing the amount of valorized waste converted into value-added products, which also has an impact on minimizing untreated waste disposed into the environment. The outcome of the EIP design in this study will contribute to maximizing added value and minimizing environmental costs. Previous studies predominantly concentrated on the context of developed countries, whereas EIP optimization within the context of developing countries was not well addressed (Perrucci *et al.*, 2022). Through a case study within Indonesia's coffee agroindustry, this study contributes to addressing the gap in the literature concerning EIP development in developing countries. Indonesia plays a significant economic role as the third largest coffee producer worldwide after Brazil and Vietnam. Coffee plantations were the third largest after oil palm and rubber plantations in Indonesia in 2021, contributing 16.15% to its gross domestic product 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 (GHG) emissions (Laili *et al.*, 2022). Coffee processing generates wastewater that contains mucus and remnants from fermentation, which is notable for its corrosive nature and high acidity (Sahana *et al.*, 2018). Similarly, solid waste such as pulp, husk, silver skin, and residues generated from fertilizers and herbicides (Chala *et al.*, 2018) contribute to soil pollution and eutrophication (Woldesenbet *et al.*, 2016). Such coffee waste leads to the emission of 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). Coffee solid waste constitutes biomass containing useful compounds, including carbohydrates, cellulose, hemicellulose, lignin, lipids, proteins, ash, caffeine, tannins, chlorogenic acids, and pectins (Nguyen *et al.*, 2019; Santos *et al.*, 2021). Such waste is potentially used as raw materials for valuable products, including biosugar, biofuel, fertilizers, enzymes, dietary fiber, and bioactive compounds (Durán-Aranguren *et al.*, 2021). Coffee solid waste comprises a substantial portion of the coffee cherry biomass during coffee processing, reaching 50% pulp and 20% husk (Arya *et al.*, 2022). Abundant coffee solid waste, including agricultural by-products, is a type of waste stream exchange common to most networks in EIP (Domenech *et al.*, 2019). The coffee agroindustry in Indonesia has the potential to be developed into an EIP through the implementation of IS. When applied in the coffee agroindustry, IS encourages coffee industries to collaborate and use one another's by-products, leading to reductions in the use of raw materials, production costs, and environmental pollution. Coffee-based EIP is designed to facilitate IS in the form of material exchange for coffee solid waste, then continue with the process of valorizing this coffee solid waste into value-added products by using certain technology. This process describes the implementation of IS in the coffee agroindustry, where coffee by-products are exchanged and become raw materials for other industries. This study aimed to analyze and develop a coffee-based EIP design through a systems engineering approach and optimization of IS in closed-loop coffee production. This study was conducted in the Ketakasi coffee-producing center, Jember Regency, in East Java Province, Indonesia from 2022 to 2023.

MATERIALS AND METHODS

East Java Province ranks as the fifth-largest coffee producer in Indonesia, and within this province, Jember Regency is known as a prominent coffee-

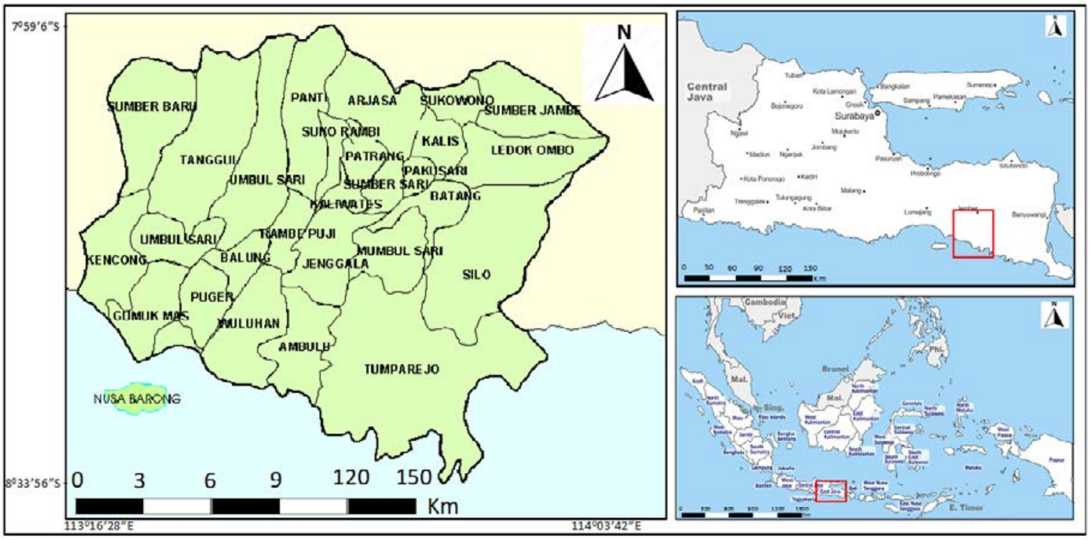

Fig. 2: Geographical location of the Ketakasi coffee-producing center in Jember Regency, East Java Province, Indonesia (red square)

producing area. This research was conducted in the Ketakasi coffee-producing center located in Sidomulyo Village, Silo District, Jember, East Java Province, Indonesia (Fig. 2). The development of EIP design followed a systems engineering methodology, as demonstrated through the utilization of Business Process Model and Notation (BPMN). Subsequently, this study optimized IS within the material exchange, delineated earlier in a BPMN-based EIP framework.

Case study location and data collection

The climate in Jember Regency, including the Ketakasi coffee-producing center, is tropical. Temperature figures range between 23 degrees Celsius (°C) and 31 °C, with the dry season occurring from May to August and the rainy season occurring from September to January. Considerable rainfall occurs, ranging from 1,969 millimeters (mm) to 3,394 mm. Geographically, the case study is located at 7°59′6″–8°33′56″ south latitudes and 113°16′28″–114°03′42″ east longitudes. The territory covers an area of 3,293.34 kilometers square (km^2), with a topographical characteristic 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 meters above sea level (masl) to 3,300 masl, with the majority of the area (37.75%) at an altitude of 100–500 masl, 17.95% at 0–25 masl, 20.70% at 25–100 masl, 15.80% at 500–1,000 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. Ketakasi is a robusta coffee-producing center with a cooperative business entity that was founded in 2007. The Ketakasi Cooperative comprises 620 farmers cultivating robusta coffee across a total area of 1,327 ha. In 2022, Ketakasi produced 2,300 tons of robusta coffee, with 95% of the output being green beans and 5% being processed coffee products. The market shares of Ketakasi's robusta coffee production, constituting 95%, is allocated for export as green beans, with the remaining 5% designated for domestic consumption. Processed coffee products for the domestic market are roasted coffee beans and ground coffee under the Ketakasi brand.

Data collection was carried out from February 2022 to March 2023 to obtain primary and secondary data. Primary data were collected through field observation techniques and a series of in-depth interviews. Comprehensive field observations encompassing the entire Ketakasi coffee agroindustry supply chain and its vicinity were conducted. This process involved the examination of coffee farmers and their plantations, the production processes within Ketakasi, the coffee processing industry/small- and medium-sized enterprises (SMEs), and the management of coffee waste and existing waste processing methods. In

Table 2: Detail of informants and interviewees in data collection

Actors	Number of interviewees
Coffee farmer	32 informants
Coffee farmer group	7 groups
Coffee industry/SMEs	18 firms
Management of the Ketakasi cooperative	3 informants
Coffee waste processor	2 SMEs
Coffee researcher from Jember University	5 informants
Researchers from the Coffee and Cocoa Research Center	3 informants
Department of Food Crops, Horticulture, and Plantation	2 informants

parallel, in-depth interviews were conducted to obtain primary data, with details of informants and the number of interviewees, as shown in Table 2. This study utilized semistructured questionnaires for primary data collection through a series of in-depth interviews. Semistructured questionnaires are a flexible data collection method commonly used in case studies because this method balances the need for specific information with the flexibility to probe further (Ruslin *et al.*, 2022). These questionnaires include a mix of predetermined questions and opportunities for open-ended responses. Semi-structured questionnaires explore certain topics in depth while keeping the structure of interviews. In this study, in-depth interviews were conducted following semistructured questionnaires in the form of a set of open-ended questions structured on the basis of seven main topics. During in-depth interviews, questions were developed to explore additional details but remained focused on the context of the seven main topics. The depth of answers of each informant differed. The seven main topics were as follows: 1) developments in the coffee supply chain and its stakeholders over the past 5 years; 2) business processes, production procedures, product transformation, and value addition of each actor in coffee supply chain; 3) sustainability pillars, including technological, social, and economic dimensions of the coffee agroindustry; 4) potential and existing coffee waste valorization process; 5) research and development activities related to coffee processing and waste valorization; 6) coffee waste generation and management; and 7) flow of materials in coffee agroindustry. The same open-ended questions were posed to multiple informants to ensure a diversity of perspectives and enhance data validation and triangulation.

Subsequently, secondary data were collected through a literature review to obtain information on EIP development, including potential by-product/waste generation and exchange, socioeconomic conditions, natural resources, technology characteristics, coffee environmental impact report, and relevant regulation and policy. These data were collected from reports of coffee farmers, coffee industry/SMEs, Ketakasi cooperative, Jember Regency government, statistical data related to the coffee agroindustry, previous studies, and other relevant documentation.

Systems engineering approach—BPMN

Systems engineering is a multidisciplined approach that integrates analytical, mathematical, and scientific principles to formulate, select, develop, and refine optimal solutions from viable candidates, considering acceptable risk, user operational needs, cost minimization, and stakeholder interests (Wasson, 2015). Regarding complexity, 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). Designing EIPs demands a comprehensive, multidisciplinary, and thorough approach, and systems engineering offers the framework, techniques, and resources needed to efficiently strategize, create, and oversee EIPs, ensuring their alignment with environmental, economic, and social sustainability goals. In this study, BPMN, a systems engineering tool, is employed to create a coffee-based EIP in Ketakasi. BPMN provides a standardized way to represent business processes, which is beneficial in the context of EIP for process visualization, process optimization, and interoperability interactions and workflows between different entities (Martins *et al.*, 2019; Schaffer *et al.*, 2021) and is essential in EIPs where multiple firms collaborate and share resources. This study uses BPMN to design EIP using the unified modeling language and SAP PowerDesigner 16.6 software.

Optimization IS—MILP mathematical model

MILP modeling is a widely recognized and established methodology employed across diverse domains to address optimization challenges, encompassing its application within the realm of IS optimization in the context of EIP. Previous studies showed that the MILP model has been implemented for water exchange in EIP in consideration of water quality (Tiu and Cruz, 2017), optimization of energy symbiotic network exchange within EIP (Afshari *et al.*, 2020; Neri *et al.*, 2023), and optimization of utility exchange between different plants within EIP (Galvan-Cara *et al.*, 2022). Most EIP optimization studies focused on optimizing one of three main categories: water, energy/heat, and materials (Boix *et al.*, 2015). Within these three categories, water exchange optimization has garnered the most extensive attention in the existing literature, whereas material exchange optimization remains less addressed (Tiu and Cruz, 2017), which is the focus of this study. Wolsey (2020) defined a general mathematical model in MILP (Table 3), typically consisting of the following components: objective function, decision variables, constraints, bounds on variables, and integrality constraint.

RESULTS AND DISCUSSION

This study undertakes the analysis and formulation of a coffee-based EIP design in Ketakasi using BPMN within a systems engineering framework. Subsequently, this study optimizes the IS, specifically focusing on enhancing the material exchange aspect within the established EIP design.

BPMN of coffee-based EIP design in Ketakasi

Ketakasi is a robusta coffee-producing center with a cooperative business entity that was founded in 2007. The Ketakasi cooperative comprises 620 farmers cultivating robusta coffee across a total area of 1,327 ha. In 2022, Ketakasi produced 2,300 tons of robusta coffee, with 95% of the output being green beans and 5% being processed coffee products. In this study, the wet processing method is used to produce coffee beans, involving a fermentation process that produced high-quality coffee beans. For every 1 kilogram (kg) of coffee cherry being processed, approximately 25%–35% is converted into coffee beans or derivative products, while 65%–75% constitutes solid waste, namely, coffee pulp and spent coffee grounds (SCG), (Fig. 3). The coffee industry also processes coffee into roasted coffee beans, ground coffee, and coffee extract and generates solid waste in the form of SCG.

This study focuses on coffee solid waste, namely, coffee pulp and SCG. The coffee pulp and SCG produced from coffee agroindustry activities in Ketakasi and its surroundings in the period 2018–2022 are shown in Fig. 4. The solid waste generated has fluctuated over the last 5 years with an increasing trend. This trend is in line with that of the national coffee production, which also tends to increase every year. During the period 2018–2022, an average of 4,760 tons of coffee pulp and 4,679 tons of SCG was generated per year. Of this amount of solid waste, only 15% was processed into animal feed and fertilizer, while 85% was untreated and disposed of in the environment. Continuously disposing of untreated coffee solid waste into the environment potentially raises environmental issues, including soil pollution and eutrophication (Capanoglu *et al.*, 2022).

Apart from abundance in quantities, the characteristics of coffee pulp and SCG as types of agricultural biomass are also indicated by the

Table 3: General mathematical model in MILP (Wolsey, 2020)

Components	Mathematical model
Objective function	Max Z = $c_1 x_1 + c_2 x_2 + \ldots + c_n x_n$
Subject to constraints	$a_{11} x_1 + a_{12} x_2 + \ldots + a_{1n} x_n < b_1$
	$a_{21} x_1 + a_{22} x_2 + \ldots + a_{2n} x_n > b_2$
	...
	$a_{m1} x_1 + a_{m2} x_2 + \ldots + a_{mn} x_n > b_m$
Non-negative restrictions	$x_1, x_2, x_3, \ldots x_n >= 0$
Decision variables	$x_1, x_2, x_3, \ldots x_n$

Fig. 3: Coffee pulp and SCG

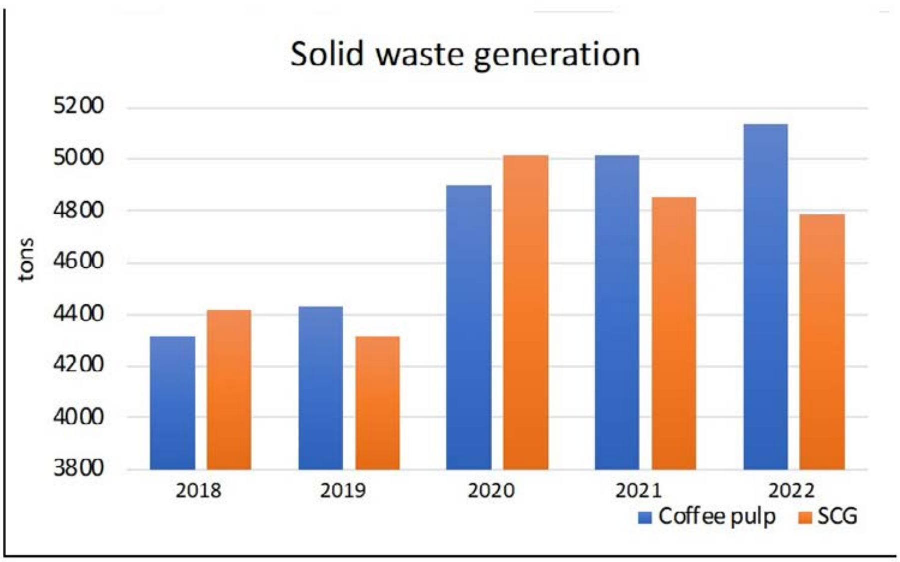

Fig. 4: Solid waste generated in the period 2018–2022

chemical compound content, such as carbohydrates, cellulose, hemicellulose, lignin, lipids, proteins, caffeine, and tannins, as detailed in Table 4. This chemical content makes coffee pulp and SCG have the potential to become raw materials for various value-added products through valorization. The chemical compounds contained in coffee pulp and SCG are determined by coffee processing methods and coffee variety (Blinova and Sirotiak, 2019).

The largest coffee-producing countries in the world are developing countries, namely, Brazil, Vietnam, Indonesia, Colombia, and Ethiopia, which export coffee in the form of green beans. Hence, primary coffee processing takes place in developing countries

Table 4: Chemical compounds in coffee waste (% dry matter) (Nguyen *et al*., 2019; Santos *et al*., 2021)

Chemical compounds	Coffee pulp	Coffee husk	SCG
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

to produce green beans. This process generates the greatest proportion of coffee waste in the form of coffee wastewater and coffee solid waste. When coffee cherries are processed to produce green beans, 65%–75% of the mass of the coffee cherries will become solid waste in the form of coffee pulp, coffee husk, and SCG. Meanwhile, developed countries, namely, the US, Canada, and European countries, are the world's largest coffee consumers. The coffee production process carried out in developed countries is secondary and tertiary production to produce roasted coffee beans, ground coffee, and extracted coffee. This process has implications for the waste produced, which is generally in the form of SCG. The generation of coffee waste is also influenced by the management and mastery of coffee waste processing technology. The presence of sophisticated waste management systems in developed countries typically allows for the systematic reduction, reuse, and recycling of coffee waste, aligning with the rigorous environmental regulations that govern waste management practices. As such, developed countries may not only generate more coffee waste but are also more likely to have established mechanisms for its efficient processing and diversion from landfills. Conversely, the coffee processing methods in developing countries often hew to traditional approaches, which may be less efficient and yield a greater quantum of waste relative to the volume of coffee cherries processed. The infrastructure for waste management in developing countries is frequently less developed, potentially leading to less efficient handling of coffee waste and greater environmental impact. Utilizing SAP® Power-Designer 16 software as the design tool, this study designs a comprehensive BPMN representation for a coffee-based EIP in Ketakasi. Fig. 5 shows the BPMN diagram, which elucidates the pertinent actors within EIP, the internal business processes of each actor, the material flows and exchanges between participants within EIP, the flows of data and information, the automated decision points at gateways, and the integration of data streams across EIP. This figure features two distinct types of flows: material flow, represented by solid lines, and data flow, depicted using dotted lines. The EIP design comprises five distinct business entities, each of which is delineated within its respective swimlane. These actors are farmers, coffee firms or SMEs, the Ketakasi cooperative, cellulase enzyme producers, and ultraviolet (UV) shield producers. The business and production activities carried out within each swimlane represent routine internal business processes specific to each actor.

Within the EIP, 620 farmers collectively have 1,327 ha of land allocated for the cultivation of robusta coffee. The internal business process of the farmers commences with the coffee harvesting process, followed by coffee processing using the wet processing method, and the production of coffee hard skin (hs), which is subsequently supplied to

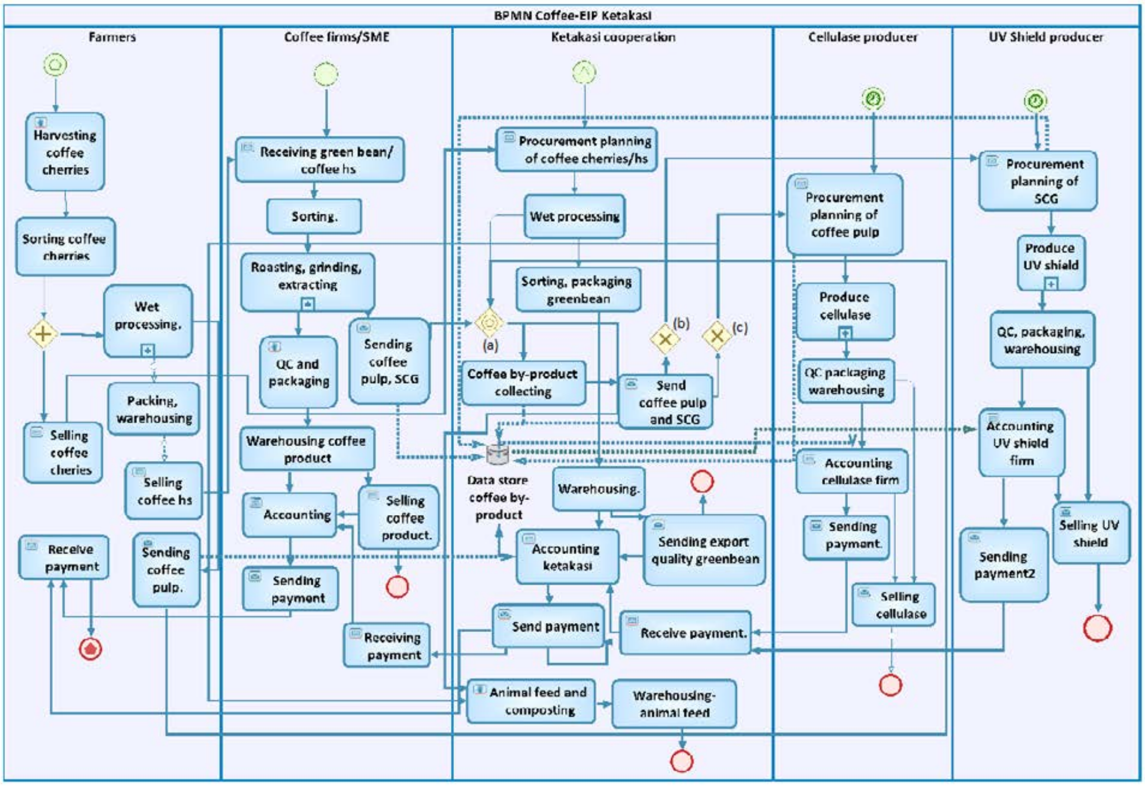

Fig. 5: BPMN of coffee-based EIP design in Ketakasi (a) gateway automation screening coffee by-product, (b) gateway SCG, (c) gateway coffee pulp

coffee firms/SMEs and the Ketakasi cooperative. Notably, because of constraints in wet processing capacity, farmers are compelled to sell a portion of their harvest in the form of coffee cherries. Within the EIP, 22 coffee firms/SMEs engage in internal business processes encompassing production processes. These processes entail using raw materials, including coffee cherries or coffee hs, to produce roasted coffee beans, coffee grounds, and coffee extracts. The Ketakasi cooperative holds a pivotal role as the EIP's manager, facilitating interactions between all EIP actors through material exchanges. The internal business process at the Ketakasi cooperative encompasses various activities, including the production of green beans for export markets, the management of coffee by-product exchanges, and the production of animal feed and fertilizers. Two actors within the EIP, namely, the cellulase producer and the UV shield producer, are actively engaged in valorizing coffee waste. The cellulase producer's internal business process involves the generation of cellulase enzymes derived from coffee pulp via a solid-state fermentation (SSF) process employing *Acinetobacter sp*. The valorization of coffee pulp into cellulase enzyme within EIP exemplifies the practice of IS, in which the by-product is treated as an input material for other production cycles. Previous studies showed that various agroindustry by-products have been valorized using different microbial strains through SSF (Sivakumar *et al.*, 2022). The critical aspect of this valorization is the selection of microbial strain, and in this case study, cellulase producers use *Acinetobacter sp*. Meanwhile, the UV shield producer's internal business process is producing UV shields or sunscreens using the extraction method, utilizing SCG as primary source material.

The dynamics of interactions among the various actors within the EIP are visually conveyed through the depiction of material and data flows traversing individual swimlanes. A comprehensive summary of

Table 5: Material exchange between actors in coffee-based EIP Ketakasi

Interactions	Material exchange
Farmers–coffee firms/SMEs	Farmers send coffee hs to coffee firms/SMEs and receive payments from coffee firms/SMEs.
Farmers–Ketakasi cooperative	Farmers send coffee cherry/green beans/coffee pulp to the Ketakasi cooperative and receive payments from the cooperative.
Coffee firms/SMEs–Ketakasi cooperative	Coffee firms/SMEs send coffee pulp/SCG to the Ketakasi cooperative and receive payments from the cooperative.
Ketakasi cooperative–cellulase producer	The Ketakasi cooperative sends coffee pulp to a cellulase producer and receive payments from the cellulase producer.
Ketakasi cooperative–UV shield producer	Ketakasi cooperative sends SCG to a UV shield producer and receive payments from the UV shield producer.

these material exchange interactions is presented in Table 5 for a thorough understanding of the inter-relationships. Material exchange processes within the EIP encompass the continuous transfer of data, as denoted by the dotted lines in Fig. 5. Notably, the Ketakasi coffee-based EIP design includes a mechanism for data integration via a “Data Store,” which serves as a central database accessible to all actors within the EIP. This “Data Store” serves as a repository for crucial information related to transactions involving coffee pulp and SCG, encompassing details such as transaction quantities and the respective payments received by each actor, enhancing transparency and facilitating efficient information exchange among EIP participants. Information-sharing platforms benefit enterprises within EIP by increasing the awareness of CE and the implementation of IS (Wen *et al.*, 2018). The design of a coffee-based EIP in this study considering the material exchange within the EIP involves the flows of data and information among the EIP’s participants. Compared with other manufacturing systems, an EIP possesses distinctive characteristics regarding the interactions within this park. The volume of data produced by each EIP participant is substantial and continually expanding, rendering conventional information management approaches impractical and ineffective for the management of EIP-related data. The development of “Data Store” in the EIP design is a solution to this need by becoming an information platform for data integration related to material exchange in the EIP. This finding aligns with previous studies indicating that the process of forming material exchange within EIP is through gathering and sharing relevant information among EIP’s participants (Wangdi and Nepal, 2018). The cellulase producer and UV shield producer, responsible for the valorization of coffee waste, input aggregate demand data for coffee pulp and SCG, as well as their weekly distribution, into the “Data Store.” This repository is accessible to all stakeholders within the EIP, including farmers and the coffee industry/SMEs. Farmers and the coffee industry/SMEs, who supply coffee pulp and SCG, deliver coffee waste to the Ketakasi cooperative and subsequently verify the compilation of data in the “Data Store.” This platform enables farmers and the coffee industry/SMEs to track the extent to which their coffee pulp and SCG meet the set valorization quality standards. Accessible data include not only the quantities of materials exchanged but also the prenegotiated prices, allowing for an estimation of expected payments. In turn, cellulase and UV shield producers utilize the “Data Store” to monitor the actual supply against their operational forecasts and adjust production accordingly. The Ketakasi cooperative, functioning as the EIP’s manager, oversees these material exchanges and manages financial transactions, issuing invoices based on the “Data Store” records. These invoices prompt payments to the cellulase and UV shield producers, which are then allocated to the respective farmers and coffee industry/SMEs as payment for their coffee pulp and SCG in accordance with the data recapitulation in the “Data Store.” The Ketakasi cooperative employs the “Data Store” not only to ensure the management of material exchange quantities and financial transactions but also to uphold the quality assurance standards for the exchanged coffee by-products. The “Data Store” is crucial in this coffee-based EIP design and becomes an information platform fostering transparency and accessibility of information among EIP participants. This finding aligns with the interdependency relationship among participants within EIP that is explicitly specified on information bases, which presents the requirement for information platforms to bind scattered information as a whole (Zhou *et al.*, 2017). Implementing the “Data Store” facilitates data integration, thereby enhancing the ability of the Ketakasi cooperative to fulfill its responsibilities within the context of the EIP in an optimal manner. These data flows signify the importance of information and communication in facilitating efficient and coordinated material exchange (Boukhatmi *et al.*, 2023). Data integration and transparency enhance the predictability and reliability of material exchange processes and circularity toward CE (Bressanelli *et al.*, 2022). Within the EIP design, three pivotal gateways are integrated, defined as tasks encompassing regulations governing material exchange. These gateways include the automation screening by-product, the SCG gateway, and the coffee pulp gateway. The material exchange starts when farmers deliver coffee pulp to the Ketakasi cooperative warehouse after completing the pulping process. This delivery is conducted either on an individual basis or collectively, contingent upon the proximity and synchronicity of other farmers’ delivery schedules. Coffee industries/SMEs deliver SCG after completing the production process. On average, the by-products from coffee processing total 308 tons of coffee pulp and 239 tons of SCG per week. Upon arrival, the Ketakasi cooperative undertakes a quality assessment of the coffee pulp, employing automated sorting gateways that evaluate parameters such as potential hydrogen (pH) levels and water content. The coffee pulp that conforms to the predefined criteria is then stored, while the noncompliant pulp is redirected for use in fertilizer and animal feed production facilitated by the cooperative. The Ketakasi cooperative delivers coffee pulp and SCG to cellulase producers and UV shield producers in alignment with the data collated in the “Data Store.” Cellulase producers and UV shield producers utilize coffee pulp and SCG as raw materials for their production processes. The material exchange process operates continuously and dynamically in accordance with the business processes of each EIP participant. For IS optimization, the MILP mathematical model is employed. The subsequent section will provide an in-depth exploration of this optimization approach. In this study, the BPMN of coffee-based EIP in Ketakasi depicts closed-loop material flows to ensure that the waste from one actor becomes a valuable resource for another, facilitating circularity in material exchange (Piemonti *et al.*, 2023). For example, coffee pulp and SCG, which become waste for farmers and the coffee industry through material exchange in EIP, can become raw materials for cellulase producers and UV protector producers. The mutual benefit derived from this resource sharing not only minimizes waste but also reduces the need for resource extraction, thereby lowering the ecological footprint and resource depletion (Zhao *et al.*, 2023). This symbiotic relationship minimizes waste generation, encourages resource sharing, and exemplifies the tenets of a CE. The BPMN diagram in Fig. 5 depicts the actors, internal business processes, material and data exchanges, various actors’ interdependence and critical roles in material exchanges, and value creation processes through valorization within the EIP. The cellulase and UV shield producers valorize coffee waste by producing valuable products. Their interest lies in securing a consistent supply of coffee waste materials, such as coffee pulp and SCG, to support their production processes. These processes contribute to environmental sustainability by reducing waste and offering economic benefits to actors engaged in the valorization process (Mendez-Alva *et al.*, 2021). The EIP design adds a new layer of economic and environmental sustainability by deriving value from materials that might otherwise be considered waste. The Ketakasi cooperative plays a multifaceted role as a manager of EIP. Their objectives encompass facilitating smooth material exchange among actors, ensuring the availability of resources for coffee by-product management, and promoting the overall sustainability and success of the EIP. An important role of the Ketakasi cooperative in material exchanges is to manage quality control on coffee pulp and SCG to enhance acceptance levels by the cellulase and UV shield producer. The Ketakasi cooperative has the motivation to maximize coffee by-products that can be valorized, namely, by encouraging farmers to conduct proper material handling and proper treatment of coffee pulp generated during coffee processing through various education and assistance. Assistance provided by the Ketakasi cooperative includes offering sensor facilities for pH and water content and arranging the scheduling of coffee pulp deliveries from farmers to meet the requirements of coffee waste users. The implication is that the Ketakasi cooperative not only helps farmers with waste management and reduces waste that is thrown directly into the environment but also provides economic benefits for farmers from the material exchange process.

Optimization of coffee waste exchange using the MILP mathematical model

The optimization of coffee waste exchange within an EIP offers substantial economic benefits, primarily through cost reductions and the creation of new revenue streams (Hamam *et al.*, 2023). Companies can significantly lower environmental costs linked to waste disposal, such as landfill fees and transportation costs, by repurposing coffee waste as a productive resource. The transformation of coffee waste into added-value products facilitates additional income. This reimagining of waste materials enhances operational efficiency and productivity, leading to increased profitability (Ledari *et al.*, 2023). The innovation spurred by the valorization of coffee waste can open up novel markets and business opportunities, particularly in the realm of sustainable goods, attracting further investment and fostering business expansion. Economic advantages also extend to compliance and supply chain sustainability. By optimizing waste exchange, businesses within the EIP can achieve regulatory compliance efficiently, avoiding potential fines and aligning with growing consumer demand for environmentally responsible practices. On the basis of the coffee-based EIP design, this study undertakes the optimization of coffee waste exchange to enhance the operational efficiency and functionality of the EIP. The coffee-based EIP design comprises three task gateways, which function as regulatory mechanisms governing material exchange. These gateways, namely, the “automation screening by-product gateway,” the “SCG gateway,” and the “coffee pulp gateway,” as shown in Fig. 5, play distinct and essential roles in the management of material exchange processes. Such gateways are strategically coordinated and managed by the Ketakasi cooperative. The “automation screening by-product gateway” serves as an automated sorting mechanism to determine whether coffee pulp is eligible for entry into the coffee by-product reservoir. This gateway has an automated sensor system, and specific criteria govern its decision-making process. The coffee pulp can pass through and access the coffee by-product reservoir if it exhibits a pH level of at least 5 and a minimum water content of 60%. These stringent criteria have been imposed because coffee pulp must meet precise pH and water content thresholds when intended for use as a raw material in the production of cellulase enzymes. When coffee pulp fails to meet these criteria during screening at this gateway, an alternative processing route is pursued, wherein the coffee pulp is directed toward animal feed and fertilizer production. The second gateway is the “coffee pulp gateway,” which regulates the flow of coffee pulp from the by-product reservoir to be sent to the cellulase producer. Within this gateway, the conveyance of coffee pulp to the cellulase producer is contingent upon meeting two specific criteria. First, the coffee pulp must have resided within the by-product reservoir for no longer than 3 days. Second, the quantity of coffee pulp supplied should align with, and not surpass, the predetermined weekly demand for coffee pulp, a figure established by the cellulase producer in alignment with the production plan. This planning, which is executed weekly, is instrumental in determining the requisite volume of coffee pulp necessary for the given production week. The final gateway is the “SCG gateway,” which manages the sending of SCG to the UV shield producer. The requirement for this gateway is that SCG can be sent to the UV shield producer as long as the supply does not exceed the aggregate demand for SCG for that week. The main objective of IS optimization in this study is to adopt the perspective of optimizing the value creation process within EIP by fostering a closed-loop production system (Prieto-Sandoval *et al.*, 2022). Optimization of value creation is conducted through maximization of the amount of value-added product through valorization technology. The optimization model is developed using the MILP mathematical model composed of objective function, decision variables, and constraints (Wolsey, 2020). The objective function is considered to obtain the optimum solution for the maximum amount of valorized coffee pulp and SCG, which has implications for minimizing coffee waste disposed into the environment, resulting in the reduction of environmental costs. The objective function of the MILP optimization model is subject to the constraints of the three gateway material exchange rules described previously. The MILP optimization model is

Table 6: Set of subscripts and variables in the MILP model

Set	Definition
Subscript	
i	Index for week-*i*
Variables	
x_i	Coffee pulp collected for week-*i* (ton)
y_i	Coffee pulp valorized into cellulase for week-*i* (ton)
z_i	SCG valorized into UV shield for week-*i* (ton)
w_i	Coffee pulp send to animal feed and fertilizer plant for week-*i* (ton)
a_i	A binary variable, 1 if the pH minimum is 5; 0 otherwise
b_i	A binary variable, 1 if the water content minimum is 0.6; 0 otherwise
c_i	A binary variable, 1 if the maximum coffee pulp shelf life in the reservoir is 3 days; 0 otherwise
n_i	pH x_i
m_i	Water content x_i
p_i	Shelf life of coffee pulp in the reservoir (days)
Dc_i	Demand aggregate of coffee pulp for week-*i*
Ds_i	Demand aggregate of SCG for week-*i*

implemented through an inclusive material exchange design involving interdependence and mutual influence between farmers, the coffee industry, the Ketakasi cooperative, the cellulase producer, and the UV shield producer. The optimum value creation solution in this model is achieved when each actor in the EIP acquires adequate economic benefits from the material exchange process (Huong, 2023). The optimization MILP model is completed using Solver in MS Excel to obtain the optimum solution. The set of subscripts and variables used in the MILP mathematical model is summarized in Table 6.

The objective function of the optimization model employed in this study is to maximize the valorization of coffee waste into value-added products. More precisely, the goal is to maximize the valorization of coffee pulp into cellulase enzymes and SCG into UV shields by using Eq. 1 (Kantor *et al.*, 2020).

Objective function:

$$\text{Max } Z = \sum_{i=1}^{n} (ai.bi).xi + ci.yi + zi + wi \qquad (1)$$

The constraint imposed on the "gateway automation screening by-product" necessitates that, for passing into the coffee by-product reservoir, the coffee pulp must exhibit a minimum pH of 5, as specified in Eq. 2, and have a water content of no less than 60%, as indicated in Eq. 3; Eqs. 2 and 3 are developed on the basis of previous research on cellulase production valorized from coffee pulp (Selvam *et al.*, 2014).

Subject to constraint:

$$\text{IF } n_i \geq 5 \text{ THEN } a_i = 1, \text{ ELSE } a_i = 0 \qquad (2)$$
$$1 \leq n_i \leq 14$$

$$\text{IF } m_i \geq 0.6 \text{ THEN } b_i = 1, \text{ ELSE } b_i = 0 \qquad (3)$$
$$m_i \geq 0$$

The constraint governing the "gateway coffee pulp" states that coffee pulp sourced from the Ketakasi cooperative will be delivered to cellulase producers under the conditions that the coffee pulp's shelf life in the reservoir does not exceed 3 days, as stipulated in Eq. 4 developed with reference to (Saldana-Mendoza *et al.*, 2021), and the quantity of coffee pulp supplied does not surpass the aggregate demand for that particular week, as indicated in Eq. 5 (Wolsey, 2020). Meanwhile, the "gateway SCG" constraint indicates that SCG can be sent to the UV shield producer if the amount of SCG supply does not exceed the aggregate demand for that week, as shown in Eq. 6 (Kanlayavattanakul *et al.*, 2021).

$$\text{IF } p_i \leq 3 \text{ THEN } c_i = 1, \text{ ELSE } c_i = 0 \qquad (4)$$
$$p_i \geq 0$$

$$y_i \leq Dc_i \qquad (5)$$
$$Dc_i \geq 0$$

$$z_i \leq Ds_i \qquad (6)$$
$$Ds_i \geq 0$$

Eq. 7 (Wolsey, 2020) defines the capacity constraint of the coffee by-product reservoir, imposing a limitation such that the combined storage of coffee pulp and SCG in a given week should not exceed 520 tons.

$$x_i + z_i \leq 520 \quad (7)$$

Subject to constraint:

$Eqx_i \geq 0$

$z_i \geq 0$

Eq. 8 represents a logical constraint, specifying that the quantity of coffee pulp valorized and the amount directed toward the animal feed and fertilizer plant must not surpass the initial amount of coffee pulp collected (Wolsey, 2020)

$$w_i + y_i \leq x_i \quad (8)$$

$w_i \geq 0,\ y_i \geq 0,\ x_i \geq 0$

The validation of the MILP optimization model in this study is conducted by optimality gap analysis. The optimality gap quantifies the difference between the current best solution and the best-known upper bound for the maximization problem or lower bound for the minimization problem on the optimal solution. The optimality gap is a measure of how far the current solution is from the best possible solution. This gap is typically expressed as a percentage and is calculated for maximization problems using Eq. 9 (Shekeew and Venkatesh, 2023).

$$\text{Optimality Gap} = \frac{Upper\ bound - Curent\ optimum\ solution}{Upper\ bound} x100\% \quad (9)$$

The optimization model is then completed using data collected over a period of 5 months of observations in the case study. The optimization objective function is completed using Solver in MS Excel, and the result is presented in Fig. 6. The optimization result presented in Fig. 6 depicts a comparison between the actual coffee waste generated and the potential waste amenable to valorization within the EIP, encompassing coffee pulp and SCG. Coffee pulp and SCG generated for 21 weeks show fluctuations every week. Coffee processing in Ketakasi generates 252–376 tons of coffee pulp per week and 181–317 tons of SCG per week, as depicted in a blue graph in Fig. 6. The MILP model optimization results are shown in an orange graph, which represents the optimum amount of valorized coffee pulp and valorized SCG each week. Fig. 6 compares the optimum amount of valorized coffee pulp and the total coffee pulp generated, as well as the optimum amount of valorized SCG and the total SCG generated. The average amount of coffee pulp generated from coffee processing is 308 tons per week, while the average optimization result for the amount of valorized coffee pulp is 72.3% at 224 tons per week. This MILP optimization model is validated using Eq. 9, and an optimality gap of 9.67% is obtained. This percentage of optimality gap implies that the current optimum solution's valorized coffee waste is 9.67% less than the best-known upper bound on the maximum valorized coffee waste that could potentially be achieved. The optimization results show that not all coffee pulp can be valorized into cellulase enzymes and processed into fertilizer and animal feed. Likewise, the average amount of SCG generated is 239 tons per week, while the average optimization result for the amount of valorized SCG is 164 tons per week or approximately 68.5%; the remainder is

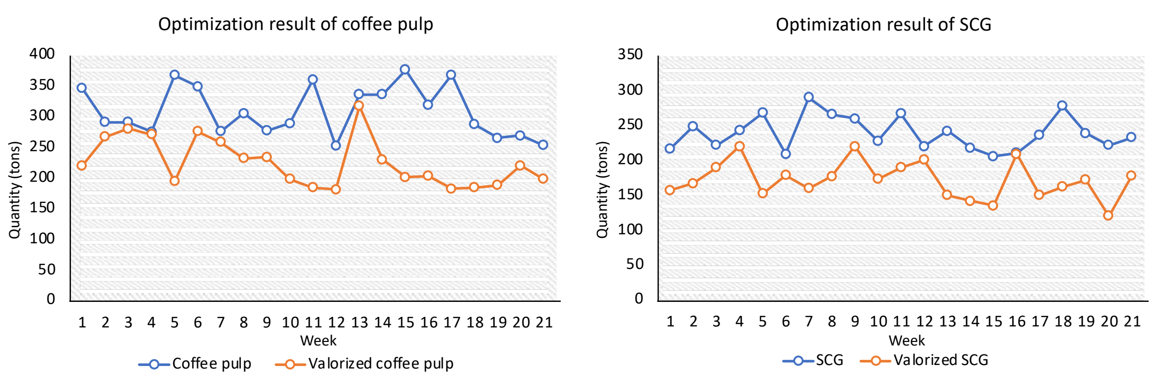

Fig. 6: Optimization result of material exchange for coffee pulp and SCG

disposed of into the environment. The comparison result indicates that material exchange in coffee-based EIP is capable of facilitating the value creation process. A total of 72.3% of coffee pulp is valorized into cellulase enzymes, and 68.5% of SCG is valorized into UV shield, which illustrates the value creation process. Coffee pulp and SCG, which are initially by-products with no economic value and causes emissions, undergo a valorization transformation into cellulase enzymes and UV shields with economic added value. Valorization of coffee pulp and SCG shows that the EIP design is also capable of facilitating IS optimization, in which by-products from farmers and coffee SME/industries become raw materials for cellulase and UV shield producers (Noori *et al.*, 2023). In this study, cellulase producers have a tendency to increase their production capacity with the intention of increasing the amount of coffee pulp demand. The relatively low price of coffee pulp compared with that of the original raw material is the main motivation for cellulase producers. This condition demonstrates the interdependence among EIP stakeholders with disparate interests, ultimately influencing the overall performance of the EIP, particularly with respect to optimizing material exchange and enhancing value through valorization (Bastias *et al.*, 2023). The MILP optimization model in this study is inclusive, in which every coffee by-product producer and processor receive economic benefits as an outcome of the material exchange process. Farmers and coffee industries, which are the coffee pulp and SCG producers, receive payments from the material exchanges. The inclusive MILP optimization model in this study facilitates payment agreement of coffee by-products between farmers and SMEs/coffee industry with cellulase and UV shield producers through the intermediary Ketakasi cooperative as EIP manager. This finding contributes to providing an appropriate scheme for a proper benefit for all participants in EIP, considering that in EIP practices, the greatest plants are usually the ones that obtain the highest benefits (Juarez-Garcia *et al.*, 2020). Meanwhile, cellulase producers and UV shield producers acquire access to cheap raw materials. This finding strengthens previous studies indicating that the competitive price factor of raw materials originating from by-products is one of the determinants in optimizing IS in EIP (Huang *et al.*, 2020). The percentage of valorized coffee pulp and valorized SCG shows a reduction in coffee solid waste disposed into the environment, resulting in decreased environmental impacts.

The discrepancy between the aggregate generation of coffee solid waste and the optimized valorization outcomes signifies the proportion of coffee solid waste designated for conversion into fertilizer and animal feed. This disparity highlights the existing opportunities for enhancing value creation in the advancement of EIP. Various factors, including coffee pulp failing the screening criteria associated with pH and water content, contribute to this disparity. Should coffee pulp fail to conform to the specified pH and water content criteria, farmers can pursue improvements as the main producers of coffee pulp. Farmers can implement various alternative improvements, such as refining the post-production material handling of coffee pulp and optimizing the scheduling of coffee pulp deliveries to the Ketakasi cooperative. The strong motivation among farmers to enact these improvements stems from the prospect of realizing augmented income by adhering to the cellulase producer's requirements regarding pH and water content. This finding underscores the influential role of material exchange within the EIP, fostering a climate that incentivizes and propels internal business process adjustments among the key actors in the EIP (Komkova and Habert, 2023). The interdependence observed among the actors within the EIP underscores the complexity of managing diverse interests while striving for the collective goal of enhancing the EIP's performance. This disparity is also caused by the constrained valorization of coffee pulp and SCG due to the production capacity of cellulase and UV shields, as limited by the weekly aggregate demand for coffee pulp and SCG. Increasing the production capacity of cellulase and UV shield potentially increases the valorization process and reduces the solid waste disparity. Another alternative is adding flow material exchange to produce new valorization products aside from cellulase and UV shields. This step can be realized by adding actors to the EIP who function as coffee pulp and SCG processors, but this alternative requires an investment decision. The findings presented in this paper unveil a structured approach to enhancing the operational efficiency and overall functionality of an EIP regarding coffee waste valorization. Through the BPMN and subsequent optimization of the EIP, this study elucidates a framework that effectively manages material exchange and value creation processes, contributing to environmental sustainability and economic value creation. The environmental impact is decreased owing to reduced disposal of coffee pulp and SCG directly into the environment. This study identifies an increase in coffee pulp valorization from 15% to 72.3% and SCG from unvalorized to 68.5% valorization. The percentage of valorized coffee pulp and SCG also represents a reduction in the percentage of coffee solid waste that is disposed of into the environment. This reduction in solid waste disposal will have an impact on reducing waste landfills, soil pollution, eutrophication, and other related environmental impacts. Environmental benefits also result from the low raw material consumption for cellulase and UV shield production. This condition complies with the reuse of coffee by-products recovered and optimizes natural resource use through the circulation of high-utility materials. The environmental benefits also include a decrease in hazards to the environment, especially in terms of waste disposal and emission of GHG caused by coffee solid waste. The implication is a reduction in environmental costs that must be borne by the coffee agroindustry. These resultant environmental benefits will enhance the environmental sustainability of the Ketakasi coffee agroindustry and its surroundings. This finding aligns with previous studies on the implementation of EIP, raising environmental benefits primarily from the reduction of pollutant emissions to the environment and the exploitation of raw materials from natural resources (Kowalski *et al.*, 2023). This study identifies challenges in implementing IS within the coffee-based EIP. The first challenge is the difficulty in developing the coffee waste valorization industries/SMEs. The development of the coffee waste valorization industry requires institutional settings and investment decisions (Maryev and Smirnova, 2021). An alternative solution for this challenge can be developed through public–private partnerships involving local government and private industry, such as offering incentives for companies that use coffee waste raw materials for their production. The second challenge is the existence of a trust issue between EIP participants because by carrying out material exchange in the EIP, these companies must share sensitive company information related to their production processes. Alternative solutions that can be implemented are establishing a company confidentiality agreement or developing a subsidiary as a coffee waste processor so that trust can be achieved in a way that company secrets will be protected. Based on the findings in this study, several practical recommendations emerge for stakeholders, policymakers, and practitioners in the domain of EIP development. For stakeholders, the pivotal role of a central management entity, as exemplified by the Ketakasi cooperative, cannot be overstated; such an entity should be instituted to steer material exchanges and oversee EIP operations. The success of an EIP is inextricably linked to the strength of its information and communication infrastructure. Thus, stakeholders must prioritize the establishment of robust networks that enable seamless sharing and coordination. For practitioners, the application of structured mathematical models, such as the MILP model deployed in the study, should be replicated to enhance the valorization process, thereby contributing to the EIP's sustainability and economic viability. Practitioners must engage in meticulous planning and management to adeptly navigate the complexities of production demands within an EIP framework. For policymakers, the findings in this study contribute to developing regional planning policies and regulations toward CE through the development of EIP. For future EIP designs, this study illustrates the potential of EIPs to maximize the value creation process by applying the MILP mathematical model to optimize the valorization of coffee waste. This structured approach to managing material exchange processes contributes to environmental sustainability and economic value creation, providing a strategic framework that can be adapted to future EIP designs in various sectors.

CONCLUSION

This study has comprehensively analyzed and formulated a coffee-based EIP design in Ketakasi, utilizing BPMN within a systems engineering framework. The BPMN diagram illustrates the EIP design and presents the actors, internal business processes, material and data exchanges, various actors' interdependence and critical roles in material exchanges, and value creation processes using valorization within EIP. The role of the Ketakasi cooperative as a facilitator of material exchange and manager of the EIP is pivotal. The use of a "Data Store" for data integration enhances the transparency and efficiency of information exchange among EIP participants, promoting predictability and reliability in material exchange. This research underscores the importance of information and communication in the success of EIPs, ensuring the sustainable management of resources and materials. The cellulase producer and UV shield producer's valorization of coffee waste sets an example of how resource sharing can lead to economic benefits and reduced waste, aligning with the principles of a CE. The application of the MILP mathematical model has provided a structured approach to maximizing the valorization of coffee waste into value-added products, specifically cellulase enzymes and UV shields. The objective function seeks to optimize this valorization, ultimately contributing to reducing coffee waste disposal into the environment. A total of 72.3% of coffee pulp is valorized into cellulase enzymes, and 68.5% of SCG is valorized into UV shield, which illustrates the value creation process. This study emphasizes the interconnectedness of the EIP stakeholders and their diverse interests. The success of material exchange within the EIP is contingent on the rigorous criteria set for coffee pulp and SCG and the weekly production planning and capacity of the cellulase and UV shield producers. This interdependence emphasizes the complexity of managing diverse interests while collectively striving to enhance the EIP's performance. This paper presents a structured framework for efficiently managing material exchange processes within an EIP, contributing to environmental sustainability and economic value creation. By optimizing coffee waste exchange, this study demonstrates the potential of EIPs to minimize waste and enhance resource valorization, thus aligning with the principles of a CE and promoting the responsible management of valuable resources. This study contributes to the knowledge gap in the literature by developing an inclusive EIP design that facilitates the optimization of the value creation process through valorization technology. Based on the findings in this study, several practical recommendations emerge for stakeholders, policymakers, and practitioners in the domain of EIP development.

AUTHOR CONTRIBUTIONS

N. Laili contributed to data collection, field observation, EIP design, MILP modeling, and manuscript preparation and revision. T. Djatna, the corresponding author, contributed to improving the EIP design, supervised MILP modeling, and enriched the discussion. N.S. Indrasti supervised the data collection and analysis, oversaw the manuscript preparation, improved the EIP design, and enriched the discussion. M. Yani supervised the data collection and analysis, oversaw the manuscript preparation, proofread the manuscript, and enriched the discussion.

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CONFLICT OF INTEREST

The author declares that there is no conflict of interest regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy, have been completely observed by the authors.

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PUBLISHER'S NOTE

ABBREVIATIONS

%	Percent
BPMN	Business Process Model and Notation
BPS	Badan Pusat Statistik
BRIN	Badan Riset dan Inovasi Nasional
°C	Degree Celsius
CE	Circular economy
EIP	Eco-industrial park
Eq.	Equation
GDP	Gross domestic product
GHG	Greenhouse gas
ha	Hectares
hs	Hard skin
ILP	Integer linear programming
individuals	Individuals
IS	Industrial symbiosis
kg	Kilogram
km	Kilometer
km²	Square kilometers
masl	Meters above sea level
Max	Maximization
Million	Million
MILP	Mixed-integer linear programming
mm	Millimeters
MINLP	Mixed-integer nonlinear programming
months	Months
MS Excel	Microsoft Excel
pH	Potential hydrogen
SAP	System application and product in processing
SCG	Spent coffee grounds
SMEs	Small- and medium-sized enterprises
sp.	Species
SSF	Solid-state fermentation
Ton	Ton
Tons	Tons
UML	Unified modeling language
UV	Ultraviolet
Week	Week

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