Spektrum Industri
Vol. 23, No. 2, 2025, pp. 306-323
ISSN 1693-6590
https://journal3.uad.ac.id/index.php/spektrum/index

Closing the Loop: Goal Programming-Based Optimization in a Tofu-Centered Agro-Eco-Industrial Park

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ARTICLE INFO

Article history
Received June 25, 2025
Revised August 1, 2025
Accepted August 11, 2025

Keywords
Agro-Eco-Industrial Park;
Goal programming;
Optimization;
Tofu industries;
Waste recycling rate.

ABSTRACT

Developing an agro-eco-industrial park based on the tofu industry must consider the balance of each agro-industry's production capacity. This research aims to (1) develop an optimization model for material flow between industries and (2) explain the material flow and provide waste utilization recommendations for other industries to create a closed loop. The industries involved in this agro-eco-industrial park consist of the tofu industry, fertilizer producers, tempeh gembus producers, cattle farms, biodigesters, paddy farmers, soybean producers, and nata de soya producers. The model was created using a goal programming approach. Traditional tofu processing typically generates a variety of waste with high nutritional value, but this waste can be detrimental to the environment if disposed of directly. The flow of materials among related industries is based on the tofu industrial cluster, which comprises 30 SMEs in Grobogan, Central Java, Indonesia. The expected output consists of eight decision variables representing the production amounts of industries. The result reveals that the model outperforms current conditions, with the waste recycling rate increasing from 14% to 97%. This contributes model converts waste into valuable resources such as fertilizer and gas energy through biodigester processing and other economically viable methods.

1. Introduction

The eco-industrial park (EIP) approach integrates two fundamental principles: developing industrial zones focusing on environmental factors and producing high-quality products that remain competitive in the market. The majority of research for establishing the EIP model was done in an industrial estate. On the other hand, the agro-industry generates large quantities of waste that can be reused. Unfortunately, the development of the EIP model for agro-industry remains underpublicized. The tofu industry is a promising example of the EIP agro-industry due to its nutrient-rich waste, which presents considerable economic potential. Tofu is primarily produced from soybeans and boasts a highly nutritious content, a straightforward production process, widely available raw materials, and a cost-effective price (Huang et al., 2022). Tofu is a traditional food renowned for its high digestibility and nutritional value, and is especially favored in Asian nations (Y. Yu et al., 2015).

https://doi.org/10.12928/si.v23i2.396

Tofu, considered a native food, is readily available to nearly everyone in Indonesia. For a one-ton basis of processed soybeans, the phases of the tofu-making process, which include soybean milling, boiling, protein coagulation, filtration, and preservation, will generate 7 to 10 tons of wastewater (H.-Q. Yu et al., 2002). Tofu consumption in Indonesia is 7.4 kilograms per person per year. According to the Agency for the Assessment and Application of Technology, for every 80 kg of tofu produced, 2,610 kilograms of waste is generated (Dianursanti et al., 2014). Indonesian Statistics showed that the weekly growth in tofu consumption has increased by 11.11% each year over the last decade (Indonesia, 2019, 2020)

The tofu production process generates a variety of solid waste and liquid waste. The filtration and clumping process generates solid waste, which can still be processed into value-added products such as tempeh (Khairani et al., 2019), animal feed (Mulyasari et al., 2022), and crackers. Waste from tofu production can be repurposed into key ingredients for bread production (Hikmah et al., 2019). Liquid waste is produced from washing, boiling, pressing, and molding tofu, which contains a high concentration of organic compounds and nutrients (Elystia et al., 2023), such as carbohydrates (25%-50%), fat (10%) (Safrilia et al., 2021), proteins, and lipids (226,06 mg/L - 434,78 mg/L, approximately 40-60%) (Dianursanti et al., 2014), along with nitrates and phosphates (Pramudyanto & Nurhasan, 1987).

Tofu-processing wastewater contains significant levels of BOD (Biochemical Oxygen Demand), COD (Chemical Oxygen Demand), TSS (Total Suspended Solids), and pH (Acidity) that exceed the threshold of environmental safety (Rajagukguk, 2020). The conversion of these organic compounds into biogas through anaerobic processes (Faisal et al., 2016) shows conversion rates up to 50% in methane gas production (Nurjuwita et al., 2021). Liquid waste is considered more hazardous than solid waste, and if discharged immediately into water, it will reduce the environment's assimilative capacity (Nandomah & Tetteh, 2023). Although residents are aware of the negative impact of pollution on the ecosystem, they are not yet concerned because it does not directly affect their community (Nugroho et al., 2019). The Environmental Performance Index (EPI) of traditional tofu production was measured at -3.94, indicating that its environmental performance falls below the acceptable quality standard threshold (Septifani et al., 2018).

The tofu industry in Indonesia is still dominated by small and medium-sized enterprises (SMEs) that require additional funding to ensure safe and compliant liquid waste management (Lusiana & Prasetiya, 2020). This leads to the discharge of substantial volumes of wastewater, posing a significant threat to the pollution of Indonesia's rivers. Tofu Whey Wastewater (TWW) is abundant, nutrient-rich, and safe since it contains oligosaccharides, proteins, oligopeptides, and phytochemicals such as isoflavones, saponins, and phytic acid, among other substances (S. K. Wang et al., 2020).

TWW is an excellent alternative medium for cultivating some freshwater microalgae cultures, such as Chlorella pyrenoidosa (Y. Wang et al., 2019), Schizochytrium sp. (S. K. Wang et al., 2020), and Chlorella vulgaris (Dianursanti et al., 2014). The production of docosahexaenoic acid (DHA, C22:6n−3) is carried out by Schizochytrium sp, and its presence is essential for maintaining optimal neurological and visual system functioning in humans (S. K. Wang et al., 2020). Several attempts have been made to utilize TWW as a medium for manufacturing a variety of products, including vitamin B12 produced by Propionibacterium freudenreichii, lactic acid produced by Streptococcus bovis, and biohydrogen produced by Rhodobacter sphaeroides (Y. Yu et al., 2015; Yuwono & Kokugan, 2008). Furthermore, tofu liquid waste and coconut water can be used to produce nata de soya products. Liquid waste from tempeh production exhibits the same characteristics as tofu wastewater and can be used as a raw material for processed food products, such as nata de soya (Azizah et al., 2022).

This research aims to (1) develop a goal programming-based optimization model that accounts for material flow interactions within the tofu industry, and (2) map the material flow and propose recommendations for waste utilization to support the establishment of a closed-loop system. This model was developed using goal programming to optimize the material utilization. Goal programming is employed to balance the production capacities of the participating industries. An imbalance in capacity can lead to inefficient material exchange, resulting in shortages for some industries and excess residual waste for others. This model is designed to provide a production capacity plan for each industry within the tofu-based Agro-Eco Industrial Park (AEIP), aiming to achieve optimal overall system performance.

Research on Eco-Industrial Parks (EIPs) can be categorized into several main areas: (1) development of EIP conceptual models (Côté & Cohen-Rosenthal, 1998; Eilering & Vermeulen, 2004; Haskins, 2007; Hong & Gasparatos, 2020; Tellier et al., 2017). (2) research that assesses the impact of EIP development on industry (Ashton, 2009; Zhu et al., 2015), and (3) research focused on measuring material exchanges between industries. Therefore, within the EIP research roadmap, this research is categorized under product exchange modeling using linear programming, specifically applied to the tofu industry. The originality of this mathematical model lies in the identification of unique input and output materials for each participating industry, as well as the consideration of alternative downstream industries that can utilize the processed waste from tofu production. The industrial case studies examined in EIP research predominantly focus on industries that process agricultural products (Santoso et al., 2014; Setiawan et al., 2019), industrial estates (Genc et al., 2019; Liwarska-Bizukojc et al., 2009; Roberts, 2004; Taskhiri et al., 2011) as well as the application of EIP in the palm oil industry (Foong & Ng, 2021; Purwaningsih et al., 2024; Teh et al., 2021). The development of EIP models for the agro-industry remains underreported in existing literature. The tofu industry, as a representative agro-industrial sector, offers a significant potential case due to the high economic value of its waste. Table 1 summarizes the methods and case study objects used in existing EIP model development research.

Table 1. Research Methods and Industrial Focus in EIP Model Development

Author(s) (Year)	Method	Industrial Focus		
		Palm Oil Industry	Industrial Estate	Agro-Industry
(Foong & Ng, 2021)	MILP	✓		
(Tiu & Cruz, 2017)	MILP		✓	
(Taskhiri et al., 2011)	Fuzzy MILP		✓	
(Ramos et al., 2015)	Goal Programming		✓	
(Setiawan et al., 2019)	Goal Programming			✓
(Hariz et al., 2018)	SWOT		✓	
(Cao et al., 2009)	Modelling and Simulation		✓	
(Sjaifuddin, 2020)	Dynamic System Simulation		✓	
(Teh et al., 2021)	Stability Analysis, VIKOR	✓		
(Y. Wang et al., 2019)	Grey Relational Analysis (GRA)		✓	
(Rauf, 2025)	Qualitative; Waste Exchange		✓	
(Liwarska-Bizukojc et al., 2009)	Conceptual Model, Mass & Energy Flow		✓	
(Santoso et al., 2014)	Mass Balance, Mathematical Model			✓
This Research	**Goal Programming**			✓

Goal programming has been used in previous research on industrial estates (Ramos et al., 2015) and in designing an agro-industry model (Setiawan et al., 2019). Several other studies have used the mass balance method to assess the quantity of industrial output to reduce waste (Liwarska-Bizukojc et al., 2009; Santoso et al., 2014). EIP can also be optimized using the MILP (mixed-integer linear programming) (Foong & Ng, 2021; Tiu & Cruz, 2017), another approach is fuzzy MILP (Taskhiri et al., 2011). Developing the EIP model using linear programming involves organizing activities to achieve optimal results based on a mathematical model of all conceivable alternatives (Hillier, 2009). Charles and Cooper established the goal programming model in early 1961 as an extension of linear programming, a mathematical method used to generate an optimal solution for multi-objective decision-making. The goal programming aims to minimize deviation from the ideal solution (Lotfi et al., 2014). The deviation variables in each objective and constraint function distinguish the goal from linear programming.

Previous research in the Sugihmanik tofu industry measured environmental impacts using LCA (Hartini et al., 2021). Tofu production efficiency was also measured using value stream mapping, resulting in a low efficiency value of 71%, due to unrecycled waste material that is discarded into the environment (Hartini et al., 2021). Expanding upon previous research, this research aims to optimize material utilization to achieve a high recycling rate within the tofu industry. The originality of this research lies in the development of a goal programming model tailored explicitly for an agro-industrial eco-industrial park (AEIP) based on the traditional tofu industry. Unlike previous studies that focus primarily on industrial estates or generalized material flows, this study identifies detailed input–output material exchanges between interconnected small-scale industries. In particular, the model incorporates unique backward industries, such as cattle farming, fertilizer production, and tempeh gembus processing, that utilize waste from the tofu industry as input.

2. Method

2.1. The Flow of Materials in The Tofu Industry

The focus of this research is the tofu industrial center in Sugihmanik Village, Grobogan District, Central Java, with 30 SMEs producing 270 kg of tofu per day. According to the test results, the liquid waste contains BOD5 at 4933 mg/L and COD at 7668.33 mg/L. These values exceed the threshold values set by Central Java Regional Regulation Number 5 of 2012, which are 150 mg/L for BOD5 and 275 mg/L for COD. River water in Sugihmanik Village had a BOD5 value of 367 mg/L and a COD value of 738 mg/L, both of which exceeded the threshold (Hartini et al., 2021). Fig. 1 shows materials flow in the AEIP model of the tofu-based industry.

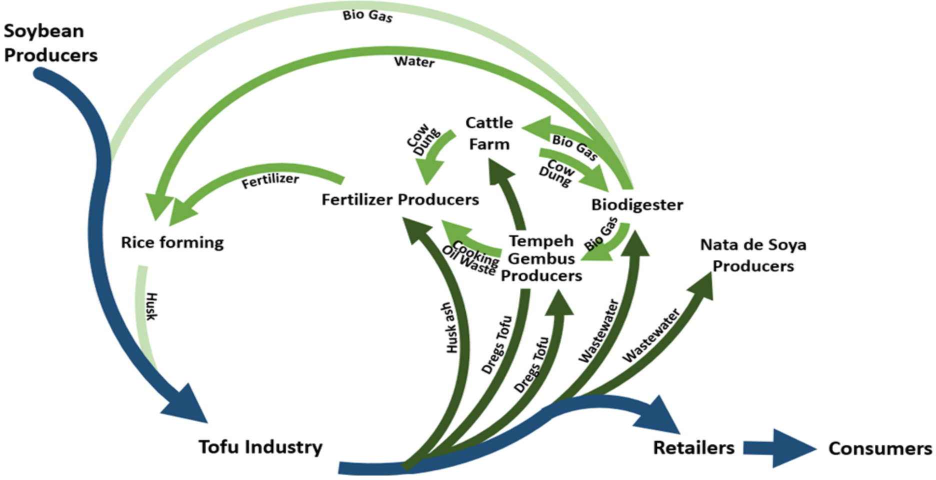

Fig. 1. Material Flow. In the context of an Eco-Industrial Park (EIP), multiple material exchanges take place across interconnected industries

Fig. 1 illustrates the flow of materials, water, and energy within the tofu industry. In the context of an Eco-Industrial Park (EIP), multiple material exchanges take place across interconnected industries. Soybean traders supply soybeans to the tofu industry as a primary input. Husk ash generated from the production process is transferred to fertilizer producers, who in turn supply fertilizer to rice farmers. Used cooking oil from tofu production is also exchanged with fertilizer producers.

Additionally, tofu dregs are utilized as feedstock by cattle farms and tempeh gembus traders. Cattle farms further contribute to the system by supplying cow manure to both biodigester units and fertilizer producers. The tofu industry’s liquid waste is distributed to biodigester units and nata de soya producers. Moreover, water recovered from biodigester operations is reused by cattle farms and rice farmers. The potential end products of this integrated system include tofu pong, tempeh gembus, nata de soya, fertilizer, animal feed, and energy generated through bio digestion.

2.2. Goal Programming Model

The development of a goal programming model to determine the balance of input and output materials in the tofu-based industry has four steps: (1) Measure volume of material input and output, (2) Formulate goal programming model, (3) Data processing, and (4) The analysis of the goal programming results focuses on three key aspects: the optimal production capacity for each industry, the deviation values indicating the extent to which goals are unmet or exceeded, and the percentage of waste recycling achieved within the system.

2.3. Goal Programming Model Variables

The conceptual model is based on data related to the ecosystem, providing an overview of the energy and material flow system between the tofu industry and other industries. The following conditions were used in the modeling of this study: the use of corn cobs as a combustion material will be converted into biogas; the remaining cooking oil used in the tofu frying process will be reused for subsequent frying; and tofu dregs can be used as animal feed and as a material for tempeh gembus production.

Table 2. Variables Value

Parameter		Unit	Notation	Coefficient
Water Requirement & Availability	Cattle Clean Water Requirement	L/head/month	a4	1200
	Paddy Irrigation Water Requirement	L /kg/month	a6	3659.88
	Availability of Irrigation Water	L /month	A6	77760000
Liquid Waste Requirement	Liquid Waste Requirement for Biodigester	L/ m^3 /month	a5	60
	Liquid Waste Requirement for *Nata De Soya*	L /kg/month	a7	9.09
Material Requirement	Soybean Requirement per kg Tofu	kg/kg/month	b17	0.56
	Husk Ash Requirement	kg/kg/month	b21	0.03
	Leftover Cooking Oil Requirement	L /kg/month	b23	0.50
	Cow Dung Fertilizer Requirement	L /kg/month	b24	0.88
	Tofu Dregs Requirement per kg of Tempeh Gembus	L /kg/month	b31	2
	Tofu Dregs Requirement per Cow	kg/head/day	b41	300
	Cow Dung Requirement for Biogas	kg/ m^3 /month	b54	30
	Fertilizer Requirement per Month for Paddy Farming	kg/kg/month	b62	0.08
	Chaff Requirement	kg/kg/month	e1	3.57
	Biogas Requirement	m^3 /kg/month	e3	0.20
Land Requirement & Availability	Land Requirement per kg of Paddy	Ha/kg/month	f6	0.0003
	Availability of Paddy Cultivation Land	Ha/Month	F6	2.86
Production & Waste Output	Tofu Dregs Output	kg/kg/month	m1	1.11
	Husk Ash Output per kg of Tofu	kg/kg/month	m12	0.18
	Leftover Cooking Oil Output	L /kg/month	m32	0.03
	Cow Dung Output per Head	kg/head/month	m4	240
	Husk Output	kg/kg/month	m61	0.38
	Liquid Waste Output	L /kg/month	w1	10.89
	Liquid Waste Output	L / m^3 /month	w5	71.43
Tofu Demand	Tofu Demand	kg/month	q1	8100

The model formulation was developed in response to conditions involving eight industries. The anticipated outcome comprises eight decision variables representing the production quantities of various industries, such as soybeans, fertilizer, cow manure, husk ash, leftover cooking oil, and tofu dregs, which serve as solid materials. Tofu wastewater is an example of a liquid material as input for the biodigester. Chaff and biogas are energy sources from wastewater processed in a biodigester. The production limitation is the market demand for tofu. Water demand is formulated in this model to meet the needs of paddy farming, livestock farming, and biodigester units. Table 2 shows the parameter values for the EIP optimization model.

The data in Table 2 were obtained from interviews with stakeholders, field observations, and direct measurements. The measurements depend on the type and quantity of inputs and outputs from traditional tofu processing (life cycle inventory for the production process). The measurement was replicated 30 times and was used to conduct a life cycle assessment (Hartini et al., 2021). For example, producing 9 kilograms of tofu requires 5 kilograms of raw soybeans. As stated in Table 2, 0.56 kilograms of soybeans are needed to produce 1 kilogram of tofu. The coefficient associated with this variable was calculated solely from a single production batch weighing 5 kg. However, the goal programming constraint aims to restrict production based on the demand for tofu, which amounts to 8100 kg per month. Additional factors contributing to the optimization result are the availability of clean water for the production process and agricultural land to accommodate the waste converted into fertilizer.

2.4. Formulation of The Goal Programming Model

There are six different types of goal constraints in goal programming, where the goal of each type of constraint is determined by its relationship to the goal function (Schniederjans, 1995). The classification of goal constraints used in goal programming is summarized in Table 3.

RHS (Right-Hand Side) or right side of an equation or inequality in a mathematical model is the target value to be achieved in each objective function. In mathematical models, the RHS appears to the right of the "=" or "≤" or "≥" sign and represents the desired quantity or performance target. In the goal programming model, each constraint k is allowed to deviate from its target value through the introduction of deviation variables d_k^+ (positive deviation) and d_k^- (negative deviation). The variable d_k^+ represents overachievement or surplus relative to the goal, whereas d_k^- indicates underachievement or shortage. These deviation values are minimized in the objective function. The objective function minimizes the waste of water, energy, and materials, formulated according to specific constraint functions to generate decision variables, as stated in Eq. (1).

Table 3. Constraints in Goal Programming

Goal Limitations	Deviation Variable in Objective Function	Deviation	Use of Desired RHS Value
$c_{ij}x_{ij} + d_k^- = b_k$	d_k^-	$(-)$	$= b_k$
$c_{ij}x_{ij} - d_k^+ = b_k$	d_k^+	$(+)$	$= b_k$
$c_{ij}x_{ij} + d_k^- - d_k^+ = b_k$	d_k^-	$(-)/(+)$	$\geq b_k$
$c_{ij}x_{ij} + d_k^- - d_k^+ = b_k$	d_k^+	$(-)/(+)$	$\leq b_k$
$c_{ij}x_{ij} + d_k^- - d_k^+ = b_k$	$d_k^-\ dan\ d_k^+$	$(-)/(+)$	$= b_k$
$c_{ij}x_{ij} - d_k^+ = b_k$	$d_k^+\ (artificial)$	None	$= b_k$

Objective Function:

$$Minimization\ Z = \sum_{k=1}^{t}(d_k^+ + d_k^-) \tag{1}$$

Constraint Function:

Residual Material Exchange Minimization (Eq. 2)

$$m_{ij}x_i - b_{ji}x_j + d_k^- - d_k^+ = 0 \tag{2}$$

Waste Liquid Exchange Minimization (Eq. 3)

$$w_i x_i - a_j x_j + d_k^- - d_k^+ = 0 \tag{3}$$

Energy Exchange Minimization (Eq. 4)

$$x_i - e_j x_j + d_k^- - d_k^+ = 0 \tag{4}$$

Water Availability Constraint (Eq. 5)

$$a_i x_i \leq A_i \tag{5}$$

Land Availability Constraint (Eq. 6)

$$f_i x_i \leq F_i \tag{6}$$

Demand Fulfillment Constraint (Eq. 7)

$$x_i + d_k^- - d_k^+ = q_i \tag{7}$$

The notation i refers to each industry that produces a final product in the system. The notation j denotes the industries or processes that consume materials produced by other industries. The decision variables obtained from the goal programming model represent the production volumes of tofu (X1), fertilizer (X2), tempeh gembus (X3), cattle farm (X4), biogas (X5), paddy (X6), soybean (X7), and nata de soya (X8). The objective of the decision variables is to determine the optimal production levels that minimize unprocessed waste and support efficient resource utilization within the eco-industrial park.

2.5. Data Processing

The model is solved using the simplex algorithm and the POM-QM for Windows 5 software. The model was entered by defining decision variables for each industry's production output, followed by inputting the constraint equations that represent material balances, demand fulfillment, and land limitations. In this study, no weighting or prioritization of goals was applied; all goals were treated equally, and the model sought to minimize the sum of deviation variables across all constraints. The value of the decision variable, the deviation value, and the recycling rate value are the outputs of the data processing results. The decision variable value compares the ideal solution and existing conditions in the form of the production amount. The EIP optimization model's deviation value indicates whether the remaining material is excess production (d+) or a lack of production material (d^-). The recycling rate value is required to determine the performance of the EIP system in both the existing and optimized models. The recycling rate is derived by dividing the amount of recycled waste by the total amount generated. After solving the objective function and the constraint function, as mentioned in the preceding subchapters, the values of the decision variables are obtained. The deviation value is calculated using the material exchange formulation Eq. (8) - Eq. (27) shown below.

The goal programming model for the tofu-based Eco-Industrial Park (EIP) is structured with the primary constraint centered on meeting the demand for tofu pong. Accordingly, tofu production is set equal to the specified demand. Additional constraints are formulated to align with this production level while addressing the resulting waste streams from tofu processing. The equality between production and demand is explicitly represented in Eq. (30). Soybean exchange occurs between soybean traders and the tofu industry. This exchange is designed to accommodate both positive deviations (overproduction) and negative deviations (underproduction) from the target value, which are minimized through the objective function. The soybean exchange relationship is formally represented in Eq. (8) and Eq. (9).

Soybean Exchange Eq. (8) and Eq. (9):

$$-b_{17}X_1 + X_7 + d_1^- - d_1^+ = 0 \tag{8}$$

$$-0{,}556X_1 + X_7 + d_1^- - d_1^+ = 0 \tag{9}$$

Similarly, the exchange of other materials is also subject to positive or negative deviations from the target values. The objective function minimizes these deviations to ensure optimal system performance. The corresponding equations are presented below, with the values specified in Table 2.

Husk Ash Exchange Eq. (10) and Eq. (11):

$$m_{12}X_1 - b_{21}X_2 + d_2^- - d_2^+ = 0 \tag{10}$$

$$0{,}178X_1 - 0{,}029X_2 + d_2^- - d_2^+ = 0 \tag{11}$$

Fertilizer Exchange Eq. (12) and Eq. (13):

$$X_2 - b_{62}X_6 + d_3^- - d_3^+ = 0 \tag{12}$$

$$X_2 - 0{,}076X_6 + d_3^- - d_3^+ = 0 \tag{13}$$

Waste Cooking Oil Exchange Eq. (14) and Eq. (15):

$$m_{32}X_3 - b_{23}X_2 + d_4^- - d_4^+ = 0 \tag{14}$$

$$0{,}033X_3 - 0{,}5X_2 + d_4^- - d_4^+ = 0 \tag{15}$$

Tofu Dregs Exchange Eq. (16) and Eq. (17):

$$m_1X_1 - b_{31}X_3 - b_{41}X_4 + d_5^- - d_5^+ = 0 \tag{16}$$

$$1{,}111X_1 - 2X_3 - 300X_4 + d_5^- - d_5^+ = 0 \tag{17}$$

Cow Dung Exchange Eq. (18) and Eq. (19):

$$m_4X_4 - b_{24}X_2 - b_{54}X_5 + d_6^- - d_6^+ = 0 \tag{18}$$

$$240X_4 - 0{,}882X_2 - 30X_5 + d_6^- - d_6^+ = 0 \tag{19}$$

Liquid Waste Exchange Eq. (20) and Eq. (21):

$$w_1X_1 - a_5X_5 + d_7^- - d_7^+ = 0 \tag{20}$$

$$10{,}889X_1 - 60X_5 - 9{,}091X_8 + d_7^- - d_7^+ = 0 \tag{21}$$

Water Flow Eq. (22) and Eq. (23):

This function combines the equations for liquid waste exchange and water availability.

$$w_5X_5 - a_4X_4 - a_6X_6 + d_8^- - d_8^+ = -A_6 \tag{22}$$

$$71{,}43X_5 - 1200X_4 - 3659{,}9X_6 + d_8^- - d_8^+ = -77760000 \tag{23}$$

Biogas Exchange Eq. (24) and Eq. (25):

$$X_5 - e_3X_3 + d_9^- - d_9^+ = 0 \tag{24}$$

$$X_5 - 0{,}202X_3 - 0{,}202X_1 + d_9^- - d_9^+ = 0 \tag{25}$$

Husk Exchange Eq. (26) and Eq. (27):

$$-e_1X_1 + m_{61}X_6 + d_{10}^- - d_{10}^+ = 0 \tag{26}$$

$$-3{,}565X_1 + 0{,}373X_6 + d_{10}^- - d_{10}^+ = 0 \tag{27}$$

Availability of Land to Produce Husks Eq. (28) and Eq. (29):

Land requirement parameters determine the amount of rice husk that can be produced. It is restricted by the area of land accessible for paddy cultivation and used for the husk, as indicated in Eq. (28) and Eq. (29).

$$f_6 X_6 \leq F_6 \tag{28}$$

$$0{,}0003 X_6 \leq 2{,}86 \tag{29}$$

Fulfillment of Tofu Demand Eq. (30)

Tofu pong entrepreneurs decide to be able to meet the demand for tofu pong without overproduction (d^+) or underproduction (d^-), such that tofu pong production equals demand. This condition is expressed as a function of Eq. 30.

$$X_1 = q_1 \tag{30}$$

2.6. Output Interpretation

The data analysis of goal programming results is based on two factors: (1) the deviation value, which reveals material balance, and (2) the recycling rate value. In the EIP system, the recycling rate is calculated in actual conditions and the optimization model. The recycling rate for each solid and liquid waste is calculated and averaged to obtain the cumulative value Eq. (31), Eq. (32), Eq. (33).

$$RR_{solid\ waste} = \frac{Produced\ solid\ waste}{recycled\ solid\ waste}\ X\ 100\% \tag{31}$$

$$RR_{liquid\ waste} = \frac{Produced\ liquid\ waste}{recycled\ liquid\ waste}\ X\ 100\% \tag{32}$$

$$RR_{cumulative} = \frac{RR_{solid\ waste} + RR_{liquid\ waste}}{2} \tag{33}$$

3. Results and Discussion

3.1. Material Mass Balance based on Tofu Industries

When considering the establishment of an AEIP centered on the tofu agro-industry, it is essential to assess the production capacity equilibrium of each agro-industry involved carefully. The unbalanced production capacity of each agro-industry in AEIP will lead to inefficient material utilization. On the other hand, there is a scarcity of materials required for the agro-industry. Optimal performance outcomes can be achieved if each member's production is balanced enough to accommodate and utilize the output of other members. The balance of production quantities can be achieved through the optimization of production quantities.

Therefore, to build an AEIP based on the tofu agro-industry, an optimization model is required that can represent the interactions and provide the ideal production value for all industries related to the tofu industry. The optimal solution is obtained in the form of the production capacity for each industry in the EIP model, using the simplex calculation. Table 4 compares the production amounts between the existing system and the optimization model.

The EIP optimization model aims to reduce the remaining material trade-offs. The EIP optimization model provides the most 'balanced' result with the fewest feasible residual trade-offs. A positive deviation variable (d^+) and a negative deviation variable (d^-) describe the remaining material trade-offs. Table 5 displays the deviation values obtained by the EIP optimization model.

Based on the goal programming calculation, the EIP optimization model's positive and negative deviation values in Table 5 indicate that waste in the tofu sector remains suboptimal. Industries continue to have an oversupply of materials. This model suggests converting existing waste into economically valuable products. Waste reduction practices aim to optimize consumption and production (Wijewansha et al., 2021). The reuse principle, which converts waste into new items and resources, has been identified as a significant process in maintaining industrial sustainability. When something reaches the end of its lifecycle, reusing resources promotes sustainable development and provides economic benefits (Osobajo et al., 2022). Reusing forms in the circulation of goods and materials involves the reuse of products through actions such as repair and refurbishment, the reuse of components through processes like manufacturing, and the reuse of materials through recycling (Zink & Geyer, 2017). The recycling principles involve converting discarded materials into new ones.

Table 4. Comparison of Total Production on The Existing System with The EIP Optimization Model

Industrial Material Demand	Production Amount		
	Existing	Optimization	Unit
Tofu Industry	8,100	8,100	kg/month
Fertilizer Producers	-	1,614.56	kg/month
Tempeh Gembus Producers	1,050	-	kg/month
Cattle Farm	3	30	cows
Biodigester	-	192.35	m3 /month
Paddy Farmers	9,377.35	21,240.5	kg/month
Soybean Producers	3,7125	4,503.6	kg/month
Nata De Soya Producer	-	8,431.65	kg/month

Table 5. Positive and Negative Deviation

Constraint	d^+	d^-
Soybean Exchange	-	0.0005
Husk Ash Exchange	1394.98	-
Fertilizer Exchange	0.28	-
Oil Exchange	-	807.28
Dregs Tofu Exchange	5.68	-
Cow Dung Exchange	0.09	-
Wastewater Exchange	7.54	-
Water Exchange	-	-
Biogas Exchange	-	1443.85
Husk Exchange	-	20953.79

The proposed input-output material exchange for the tofu industry is illustrated in Fig. 2. The x-value is derived from the results of the optimization process for the final product, as presented in Table 4. The values for various material exchange notations are taken from the coefficients of the variables as listed in Table 2. The starting point for reading Fig. 2 is from the soybean producer who supplies soybeans to the tofu industry. The tofu industry generates several waste products, including tofu dregs, which are utilized by fertilizer producers, tempeh gembus (a type of fermented soybean cake), and cattle feed producers. Wastewater from tofu production is used in nata de soya and biodigesters. The biodigesters then generate energy that is recovered by the tofu industry. Meanwhile, farmers use fertilizer, and agricultural husks are used as an input for the tofu industry during the soybean boiling process.

According to Fig. 2, the input-output composition of the tofu industry will be more optimal, which is proposed as a means to improve the tofu industry's growth. Because wastewater and husk ash have yet to be optimally reused, the existence of biodigesters and fertilizer producers will boost the utilization of waste generated. The dregs of tofu are used in the production of Tempeh Gembus. Tempeh Gembus is a fermented food made with tofu pulp as a substrate, with fungi as microorganisms (Gandjar & Slamet, 2012). Because it can only be preserved briefly, gembus tempeh is only produced in small quantities. Tofu oncom or red oncom produces similar results to tempeh gembus with microorganisms of the Neurospora sp. This proposed model aims to enhance the economic value of the tofu industry while mitigating environmental risks to surrounding communities and the environment, resulting from the presence of unutilized tofu industry waste.

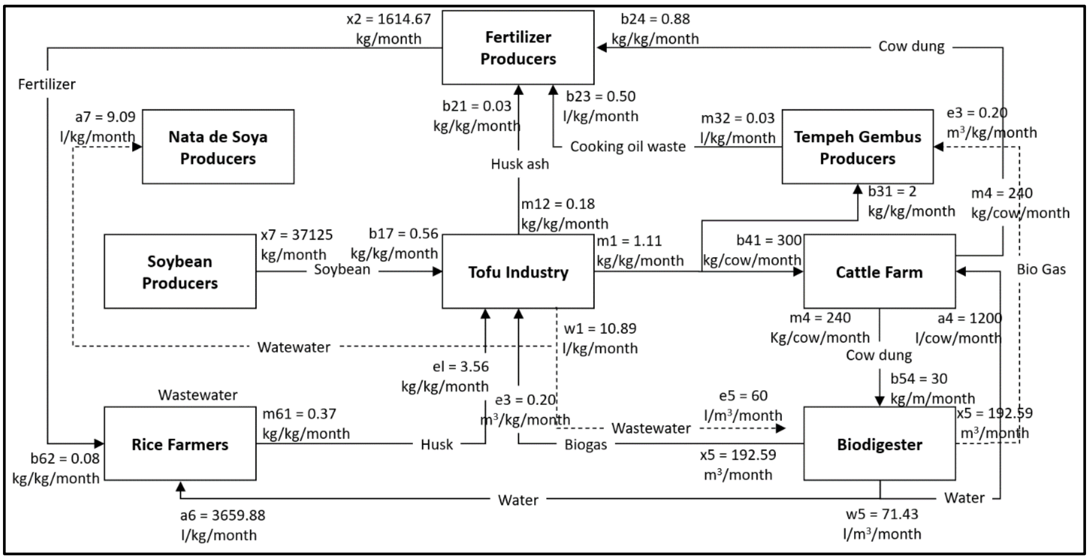

Fig. 2. Proposed Input-Output Material Composition of The Tofu Industry

The model of an eco-industrial park based on tofu industries, as described in Fig. 2, is only suitable for industries with parameter values that comply with the constraints set in the goal programming model discussed above. The number of final products and the capacity of each industry as a supplier of raw materials, representing the interlinkages among industries, can be used to develop an Agro-Industrial Eco-Industrial Park (AEIP) for a more environmentally friendly and efficient tofu-based production system. The model proposed in this study can be replicated in other locations with similar industrial capacities. To facilitate replication, the proportional relationships among related industries are illustrated in Fig. 3, where the constant values of variables have been converted into percentages for clarity.

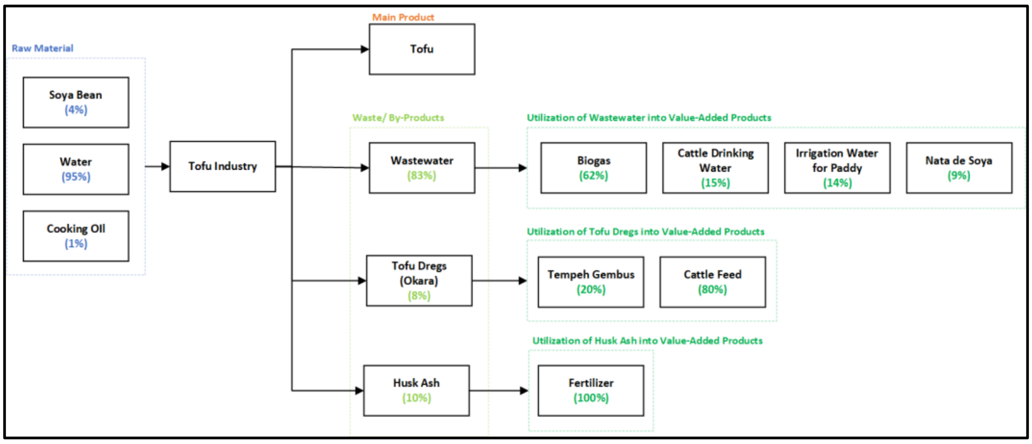

Fig. 3. Material Flow and Waste Utilization in the Tofu Industry

Based on Fig. 3, water constitutes the largest input in tofu production, accounting for approximately 95% of the total weight. Similarly, liquid waste accounts for 85% of the output. This highlights water management as the primary issue in tofu production. Further research is needed to treat and reuse wastewater into value-added products such as nata de soya or for biodigester applications. The proposed agro-eco-industrial park model still requires validation, for instance, through simulation. To evaluate its environmental benefits, tools like life cycle assessment (LCA) should be applied.

The EIP concept transforms traditional industries by advancing environmentally friendly design, architecture, construction, collaboration, and technological innovation, while enhancing business knowledge, efficiency, and economic performance, all of which contribute to environmental sustainability (Sacirovic et al., 2019). The EIP concept is an application of the circular economy concept, which aims to reuse industrial waste and minimize the amount disposed of into the environment to create a closed loop. The circular economy is characterized as a system of restorative and regenerative design. It aims to maintain products, components, and resources as valid and valuable as possible over time, distinguishing between technical and biological cycles (MacArthur, 2015). An EIP is a collection of industries that employs circular economy principles to create sustainable industries, simulates material cycles in natural ecosystems, and represents an alternative to the current industrial system (Zhao et al., 2017). EIP is an industrial or commercial park that utilizes industrial symbiosis to implement a long-term industrial ecology strategy. The concept of industrial symbiosis (IS) involves the utilization and exchange of mutually beneficial materials, enabling businesses to reduce material consumption and production costs while supporting the optimization process of EIP (Aussel et al., 2023). Closed material cycles, multiple levels of resource utilization, and waste minimization are all key objectives of this system (Organization, 2019). Pollution avoidance is a critical component of the primary industry approach to establishing eco-industrial zones (Bishop, 2000; Higgins, 1995).

3.2. Recycling Rate

The recycling rate is measured to calculate model performance at both industry and overall EIP system levels, in both the existing system and the EIP optimization model. The recycling rate is determined by the ratio of recycled waste to total waste generated. Table 6 displays the recycling rate results under current conditions and using the optimization model. Table 6 compares the production quantity under existing conditions and the EIP optimization model, revealing a considerable difference, where each industry may be more optimal in controlling its waste under existing conditions. The amount of production in the EIP optimization model is determined by optimally utilizing the waste generated by each industry based on goal programming.

Table 6. Recycle Rate Comparison

Industry	Recycle Rate	
	Existing	**Optimization**
Tofu Industry	3.03%	93.32%
Fertilizer Producers	-	-
Tempeh Gembus Producers	100%	0%
Cattle Farm	0%	96.68%
Biodigesters	-	98.60%
Paddy Farmers	100%	100%
Soybean Producers	-	-
Nata De Soya Producers	-	-
Whole System	14.14%	97.96%

The presence of fertilizer producers and biodigesters as supporting industries in the EIP optimization model results in waste and material usage optimization within the EIP system. The considerable increase in livestock demand drives demand for tofu dregs, which is expected to rise due to the large number of cattle affected by the increased utilization of cow dung as a fertilizer-making material and a source of biogas production. Tempeh gembus traders will be eliminated in the proposed EIP optimization model, as would the increasing number of cattle that require tofu dregs as feed materials, and the adoption of biogas in the tofu industry as a substitute for maize stover as a tofu frying fuel. Colimoro's research on the benefits of tofu production also suggested using tofu process wastewater as a source of electricity (Colimoro et al., 2023). This finding aligns with (Faisal et al., 2016), who specialize in research on the use of tofu waste in Indonesia (Faisal et al., 2016).

According to Table 6, the overall system recycle rate in the current state is 14.14%. This score indicates that the industry still needs to be more conscious of the need to reuse waste. The paddy farmers and tempeh gembus producers have the highest recycling rate value. Tempeh gembus traders generally reuse cooking oil for further frying, while rice husks are sold to other industries for use as fuel in cooking. The recycling rate in the tofu industry is 3.03%, achieved through waste treatment efforts such as reusing leftover cooking oil for additional frying and partially selling tofu pulp as cattle feed to local farmers. The low recycling rate under current conditions indicates that recyclable or reusable waste remains largely unutilized, highlighting the need for targeted efforts to reduce residual waste generation.

The optimization model yields a recycling rate of 97.96%, indicating that the proposed recommendations have a significant impact on enhancing the waste recycling process. In the tofu industry, waste such as husk ash, tofu dregs, and liquid waste is primarily recycled into fertilizer, animal feed, and, with the help of biodigesters, biogas, as well as irrigation water for paddy fields and livestock drinking water. Cow dung, a waste generated by cattle, can be converted into organic fertilizer. The biodigester creates biogas, which the community can utilize to generate cooking fuel or electricity, and the cleaned water can be used for livestock drinking and paddy field irrigation. The husks produced by paddy farming can be sold as a fuel source.

The limitation of this research is that the optimization results only apply to the traditional tofu production process, although this can also be unique. Developing countries in Asia continue to employ traditional methods (Nugroho et al., 2019). Furthermore, the utilization of tofu dregs in the model is limited to animal feed to achieve optimal results. Although its economic value is relatively low, the production of tempeh gembus remains a common practice among local communities. In contrast, tofu liquid waste offers more diverse product options; however, this study restricts its use to nata de soya and biodigester applications. The formulation of goal programming equations relies on several assumptions that have not been thoroughly discussed. These include fertilizer requirements per hectare and rice yield per unit of land area. These parameter values were obtained solely through interviews, as no relevant literature was available in the study area.

Despite the limitations, this research has developed the optimal model of the tofu industry that extends the value chain. When considering the sustainable utilization of materials, it is essential to consider two key aspects: eco-efficiency and eco-effectiveness. Eco-efficiency is an economic and environmental efficiency index that compares economic and ecological values (Coluccia et al., 2020). In comparison, eco-effectiveness focuses on achieving greater output utilizing the same input quantity. To achieve eco-effectiveness, the solution is to extend the value chain of a product by processing it into derivative products that possess economic value. This concept is applicable to the circular economy, as characterized by eco-industrial parks (Dong et al., 2016; Gómez et al., 2018). The optimization model developed to determine the production capacity of the tofu-based industry within an eco-industrial park proved helpful in developing similar industrial strategies to achieve a high recycling rate. This approach aims to minimize waste disposal into the environment, exemplifying eco-efficiency and eco-effectiveness in the utilization of natural resources.

4. Conclusion

The goal programming model generates an optimized production plan for industries associated with traditional tofu production, taking into account constraints such as land availability and demand fulfillment. The optimization results suggest that fertilizer production should reach 1,614 kg/month; cattle farming should scale up from 3 to 30 cows due to the high availability of tofu dregs; biodigester capacity should be set at 192 m^3/month of wastewater; paddy production should increase from 9,377 kg/month to 21,240 kg/month; soybean consumption should rise from 3,712.5 kg/month to

4,503.6 kg/month; and a new product, nata de soya, should be produced at a rate of 8,431.65 kg/month. Despite these optimizations, the presence of deviation values in the model indicates surplus and shortages in material exchanges. The model has successfully increased the system's recycling rate from 14% to 97%, meaning that only 3% of materials are discharged into the environment. This AEIP-based tofu industry model demonstrates potential for minimizing waste, enhancing resource efficiency, and increasing economic value by extending value chains. However, further validation is required through system simulations and the preparation of supporting waste treatment technologies, such as biodigesters. Reassessing the environmental impact using Life Cycle Assessment (LCA) will further substantiate the model's effectiveness and sustainability.

Author Contribution: All authors contributed equally to the main contributor to this paper. All authors read and approved the final paper.

Funding: This research received no external funding.

Acknowledgment: The authors would like to express their sincere gratitude to the management and workers of the tofu industrial center in Sugihmanik Village, Grobogan District, Central Java, for their valuable cooperation during data collection and field observations. Special thanks are extended to the Research Center for Ecology and Ethnobiology, National Research and Innovation Agency (BRIN), for their insights and support during the model validation process.

Conflicts of Interest: The authors declare no conflict of interest.

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