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# Modelling the circular bioeconomy in the palm oil industry: Emerging approaches to address cattle feed shortages in Indonesia

*Atien Priyanti*[1], *Priyono*[1], *I Gusti Ayu Putu Mahendri*[2*], *Dwi Yulistiani*[3], *Hotmatua Daulay*[1], *Yuhendra*[4], *Nasir Rofiq*[5], *Astu Unadi*[6], *Uning Budiharti*[6], *Adji Parikesit*[6], *Arsyadi Ali*[7], *Edi Erwan*[7], *Muladno*[8]

[1]*Research Center for Behavioral and Circular Economics, Research Organization for Governance, Economy, and Community Welfare, National Research and Innovation Agency, Jakarta, Indonesia*
[2]*Research Centre for Macroeconomics and Finance, Research Organization for Governance, Economy, and Community Welfare, National Research and Innovation Agency, Jakarta, Indonesia*
[3]*Research Centre for Animal Husbandry, Research Organization for Agriculture and Food, National Research and Innovation Agency, Bogor, West Java, Indonesia*
[4]*Livestock and Animal Husbandry Provincial Office of Riau, Riau, Indonesia*
[5]*Research Centre for Sustainable Production System and Life Cycle Assessment, Research Organization for Energy and Manufacture, National Research and Innovation Agency, Jakarta, Indonesia*
[6]*Research Centre for Appropriate Technology, Research Organization for Agriculture and Food, National Research and Innovation Agency, Subang, West Java, Indonesia*
[7]*Department of Animal Science, Faculty of Agriculture and Animal Science, State Islamic University of Sultan Syarif Kasim Riau (Universitas Islam Negeri Sultan Syarif Kasim Riau), Riau, Indonesia*
[8]*Faculty of Animal Science, IPB University, Bogor, West Java, Indonesia*

**Corresponding author: igus021@brin.go.id*

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**Abstract:** Indonesia is presently ranked as the first crude palm oil producer in the world. However, the palm oil industry faces significant challenges, including extensive criticism related to environmental degradation and social impacts. The circular bioeconomy concept emphasises sustainable production and consumption through the repurposing, recycling, and regeneration of resources to address these challenges. Integrating palm and cattle farming represents a promising approach to enhancing resource efficiency and sustainability in agricultural systems. This study employs a system dynamics analysis to model the circular bioeconomy in the palm oil industry, with a specific focus on addressing cattle feed shortages. The results demonstrate that utilising oil palm biomass can yield a total of 21 204.52 tonnes of feed and generate a yearly revenue of USD 317 020.14. Key findings indicate that integrating palm by-products into cattle feed not only addresses feed shortages but also reduces waste and enhances overall farm productivity. The implications of this study suggest that adopting circular bioeconomy practices in the palm oil industry can promote more resilient and sustainable agricultural practices.

**Keywords:** by-products; local resources; carrying capacity; value added; system dynamics

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Indonesia is the world's largest producer of palm oil and has a large, substantial potential market for both palm oil and palm kernel oil, nationally and globally (BPS 2022). The area of oil palm plantations reached 16.8 million hectares in 2021, increasing by 5.1%/year since 2016. The rapid development of oil palm plantations involved the important roles of large private plantations (54.4%), smallholders (41.4%), and government estate (3.8%). The palm oil industry is the economic backbone of Indonesia, generating substantial revenue and making a significant contribution to the national economy. In 2022, the contribution of the plantation crops subsector was 3.76% of the total national gross domestic product (GDP), accounting for 30.32% of the overall agriculture, forestry, and fisheries sector. The palm oil industry holds a crucial role in Indonesia's economic landscape, with a total export value of nearly USD 29.75 billion (BPS 2023). Indonesia's overall palm oil exports reached a complete production volume of 46.98 million metric tonnes in 2023, representing a slight increase from the previous year (Tradeimex 2023). Moreover, Indonesia's palm oil exports held a total market share of 59% of global exports in 2023. Indonesia has been a key player in the international palm oil marketplace for many years, with large plantations spread throughout the archipelago. India is the largest export partner of Indonesia's palm oil exports, purchasing USD 4.5 billion (19.85%) from Indonesia in 2023 (Tradeimex 2023). This robust demand underscores the importance of palm oil in both local and international markets, thus highlighting its pivotal role in Indonesia's economic landscape.

Unfortunately, the palm oil industry faces significant criticism regarding its environmental, social, and economic impacts. From an ecological perspective, oil palm plantations are often associated with deforestation, habitat and biodiversity loss (Teoh 2010), increased greenhouse gas emissions (Jamaludin et al. 2019), and water pollution resulting from palm oil mill effluent (POME) (Szulczyk and Khan 2018) as well as wastewater and empty fruit bunch disposal (Saswattecha et al. 2015). These environmental concerns highlight the pressing need for sustainable practices within the palm oil industry. Economically, the palm oil industry also faces intense competition from other vegetable oils, such as soybean and rapeseed oil, which are often cheaper to produce (Mohamad and Ab-Rahim 2024). Additionally, palm oil is a key component in biofuels aimed at mitigating climate change impacts. However, the European Parliament's 2020 ban on palm biofuel imports, intended to mitigate deforestation in Indonesia and Malaysia, has added another layer of complexity to the palm oil industry (Mohamad and Ab-Rahim 2024).

Nevertheless, tremendous efforts have been taken to enhance the sustainability of the palm oil sector in terms of its environmental, social, and economic aspects. The circular bioeconomy (CBE) is an innovative concept that integrates the principles of circular economy (CE) with the bio-based economy to promote sustainable development in the palm oil industry. The CE focuses on minimising waste and maximising resource utilisation, transforming traditional linear production models into circular systems where materials are reused, recycled, and regenerated (Ellen MacArthur Foundation 2022). The CE provides a comprehensive framework for sustainability, while the CBE takes a more targeted approach, focusing on biological resources. This specialisation enables the CBE to address specific environmental challenges more effectively, such as climate change and resource depletion. Both concepts are crucial for achieving comprehensive sustainability and require integrated strategies to maximise their potential benefits (Mesa et al. 2024).

Furthermore, Yusuf and Ojedokun (2024) stated that CE aims to minimise waste and maximise resource efficiency across all sectors by promoting practices such as reuse, refurbishment, and recycling. In contrast, the CBE specifically emphasises the use of renewable biological resources to create sustainable products and processes, incorporating bio-based innovations. While the CE encompasses a broader range of materials and industries, the CBE focuses narrowly on biological resources, aiming to regenerate natural systems and reduce reliance on fossil fuels.

In recent years, the concept of the CBE has gained significant attention from policymakers, researchers, and industry stakeholders. Notably, it is viewed as a crucial strategy for achieving the United Nations' Sustainable Development Goals, particularly within the agricultural sector (Yue et al. 2021). The integration of CE principles into bio-based industries is expected to drive innovation, create new economic opportunities, and contribute to environmental sustainability (Cuadrado-Osorio et al. 2022). On the other hand, the economic transformation currently underway in Indonesia, specifically the growth in population and income, has accelerated the demand for beef production (Priyanti et al. 2015); however, this demand cannot yet be satisfied by domestic production. Instead, Indonesia must import beef to meet national demand, reaching up to 225 650 tonnes (USD 861.58 million) in 2021, a 6.7% increase from 2020 (BPS 2022). Since domestic production can only satisfy

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approximately 45% of Indonesia's demand for beef, the price of beef remains high and tends to increase annually (Agus and Widi 2018). Meanwhile, since there is no special land earmarked for livestock businesses, efforts to improve cattle feed availability can involve using agricultural by-products as feed.

One of the promising applications of the CBE is the integration of palm and cattle farming. Oil palm plantations produce a massive amount of biomass and may generate a significant number of by-products from the palm oil industry. Notably, these by-products have the potential to be utilised as cattle feed. Palm oil production generates substantial amounts of biomass residues, such as palm kernel cake (PKC), solid decanter, and fronds, which can be recycled and repurposed as livestock feed (Warly et al. 2015; Abdeltawab and Khattab 2018; Rusli et al. 2021). By integrating palm and cattle farming, it is possible to create synergies that enhance resource utilisation, reduce waste, and address the pressing issue of cattle feed shortages. This approach not only contributes to the sustainability of palm oil production but also supports the livestock industry by providing a sustainable alternative feed source.

In this study, we explore the potential of the CBE in palm-cattle integration through the application of a system dynamics approach. This methodological approach allows us to model the complex interactions and feedback loops within the integrated system, providing insights into the effectiveness of different scenarios for optimising resource use and addressing cattle feed shortages.

**Literature review**

***Overview of existing research on the CBE.*** The relationship between the CBE and the use of palm oil industry by-products for feed can be seen as a mutually beneficial cycle. The CBE is a concept that emphasises the regenerative and sustainable use of resources. It aims to reduce waste, emissions, and dependency on fossil fuels while promoting the efficient and circular utilisation of biomass and other organic materials (Ellen MacArthur Foundation 2022). Tremendous efforts have been made to enhance the sustainability of the palm oil industry, mostly in Malaysia and Indonesia, in environmental, social, and economic aspects including bioenergy, compost, animal feed production, as well as the recycling and repurposing of palm oil waste residues. At present, a greener approach to the CBE should be adopted by the palm oil industry. This concept emphasises resource-efficient production and waste minimisation whilst aiming to attain a lower production cost, mitigate negative environmental impacts, and conserve resources (Cheah et al. 2023; Rajakal et al. 2023). Fuzzy optimisation has enabled us to determine the trade-off between landfill disposal and resource circularity, thereby maximising economic value and minimising carbon emissions in comparison to other industries. The oil palm biomass value chain is also needed to support the bioeconomy concept.

Important decisions related to aspects such as production level, product transportation, palm oil mill and processing facility locations, and the degree of environmental impact should incorporate stakeholders' and experts' judgments in the value chain (Rubinsin et al. 2021). Furthermore, the rise of Industry 4.0 can also be considered since it is part of the motivation for the transition to a CE (Abdul-Hamid et al. 2020). Yeo et al. (2020) stated that as more entities become involved in the palm oil industry network, a greater variety and amount of waste products can be collected for processing and recycling. Simultaneously, more consumers can be identified to encourage the absorption of waste products as resources, as well as the development of conversion technologies. From there, a wider circularity can be formed between multiple industries by exchanging waste materials and regenerated resources, which leads to industrial symbiosis and provides a step forward in achieving the waste-to-wealth concept. Various methods have been applied to pursue the CBE in relation to the optimisation of palm oil by-products to create valuable inputs; however, this has mostly occurred in tropical countries such as Malaysia, Indonesia, Brazil, and Papua New Guinea (Table 1).

The implementation of integrated crops and livestock systems has a strong relationship with the CBE concept. The bioeconomy emphasises the sustainable use of renewable biological resources, which includes both crops and livestock. Integrated crop-livestock systems, such as cattle and oil palm plantations, involve the combined production of crops and livestock in a manner that maximises resource use efficiency and minimises waste (Chang et al. 2020; Grinnell et al. 2022). This integrated approach to farming involves utilising crop residues and by-products from one aspect of the system as inputs for another. In this case, crop residues can be used as feed for livestock, while livestock waste can be used to fertilise crops. This interconnected relationship promotes resource efficiency and reduces the environmental impacts of agricultural production.

However, certain challenges must be addressed to unlock the full potential of palm oil by-products in the CBE. These include the development of efficient and cost-effective technologies for processing

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Table 1. Circular economy opportunities with palm oil by-products

| Categories | Methods | Locations | References |
|---|---|---|---|
| CBE in the palm oil industry | resource-efficient and waste valorisation | Malaysia | Cheah et al. (2023); Rajakal et al. (2023) |
| Oil palm biomass value chains and the environment–food–energy–water | maximise profit of the value chain | Malaysia | Rubinsin et al. (2021) |
| Sustainable CE in the palm oil industry | graph-theoretic method | Malaysia | Yeo et al. (2020) |
| Optimising the breakdown of oil palm waste as animal feed | anaerobic digestion using metabolomic analysis chromatography and nuclear magnetic spectroscopy | Indonesia | Dickinson et al. (2019) |
| Challenges to Industry 4.0 in the CE: palm oil industry | interpretive structure modelling | Malaysia | Abdul-Hamid et al. (2020) |
| Valorisation of palm oil waste | pretreatment using lignocellulosic, value-added biomolecules | global review | Letti et al. (2021) |
| The potential of oil palm frond waste | biological pretreatment using isolated cellulose nanocrystals | Malaysia | Azmi et al. (2019); Ghani et al. (2017); Rusli et al. (2021) |
| Utilisation of palm kernel cake (PKC) | review on effect of feeding PKC | global review | Abdeltawab and Khattab (2018) |
| Supplementation of solid decanter | solid ex-decanter multi-nutrient block | Indonesia | Warly et al. (2015) |
| Integrated cattle and oil palm production | literature review; the nutritional quality of the undergrowth | Malaysia, Papua New Guinea, Indonesia | Chang et al. (2020); Grinnell et al. (2022) |
| Drivers and barriers to the CE in the palm oil industry | content validity index (CVI) and modified kappa method | Indonesia | Sura and Ardi (2023) |

CE – circular economy; CBE – circular bioeconomy

Source: Author's own elaboration

and converting the by-products, ensuring the quality and safety of the resulting feed and food products, and addressing potential environmental and social concerns related to increased palm oil production (Sura and Ardi 2023). The most significant barriers identified were a lack of understanding of the CE, the absence of economic benefits, and financial constraints. These factors must be addressed to successfully implement the CBE in the Indonesian palm oil industry. Overall, the relationship between the CBE and using palm oil industry by-products for feed is symbiotic. Notably, it enables the palm oil industry to optimise resource utilisation, reduce waste, and mitigate environmental impacts whilst also providing a valuable source of animal feed.

***Modelling the CBE through a system dynamics approach.*** In recent years, notable advancements have been made in exploring the CBE of the palm oil industry using the system dynamics approach. A variety of research purposes have emerged from previous studies using a system dynamics approach, including the production sustainability of the palm oil industry (Choong and McKay 2014; Ibragimov et al. 2019; Purnomo et al. 2020); supply chain management and strategies (Faeid et al. 2018; Freitas et al. 2022; Mareeh et al. 2023); enhancing the biodiesel industry (Espinoza et al. 2017; Arrumaisho and Sunitiyoso 2019) and investigations of the environmental sustainability of palm biomass (Joyosemito et al. 2014; Zahraee et al. 2019).

Applications of the system dynamics approach exhibit considerable diversity across studies. However, within CBE studies, most employed system dynamics modelling. Building upon previous studies, a combination approach involving agent-based and system dynamics modelling has been used (Choong and McKay 2014), as well as soft system dynamics modelling (Handaya et al. 2022). The predominant methodology employed in previous studies involved the formulation of causal loop diagrams and stock and flow diagrams using system dynamics modelling during the model design phase.

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Several previous studies have been conducted to advance sustainable palm oil development by optimising the increase in fresh fruit bunch (FFB) production (Choong and McKay 2014; Ibragimov et al. 2019). Extending from upstream activities to downstream and market management, supply chain management in the palm oil and biodiesel industries has also been explored (Applanaidu et al. 2015; Espinoza et al. 2017; Zahraee et al. 2019; Mareeh et al. 2023). However, despite these existing studies, comprehensive explorations of CBE that integrate oil palm plantations with other business units remain limited. Notably, oil palm plantations harbour biomass potential that can be harnessed as a source of livestock feed.

Although some earlier studies employing system dynamics modelling have delved into CE considerations, particularly in terms of product design and business model strategies for the CE, Gao et al. (2020) and Guzzo et al. (2022) have highlighted the significance of system dynamics modelling as a crucial tool in uncovering CE-related studies. However, the in-depth elaboration of research specifically addressing CBE in oil palm plantations remains relatively scarce.

***Gaps in the current literature.*** Despite a growing body of research on the CBE, several gaps remain. First, while numerous studies have explored the technical and economic aspects of using palm by-products as livestock feed (Zahari et al. 2003; Nordin et al. 2017), research on the applications of CBE in the palm oil industry remains limited. Thus, further studies are needed to create a model for the CBE associated with palm-cattle integration. Second, most existing research focuses on case studies in specific regions but has not yet used the CE concept in detail (Chang et al. 2020; Grinnell et al. 2022). There is a need for more diverse studies to understand the application of the CBE concept in the palm oil industry.

Third, although system dynamics analysis has been recognised as a valuable tool for agricultural system optimisation, its applications in the CBE model remain limited. Therefore, further research is needed to develop comprehensive dynamic models that accurately capture the complexities of integrated farming systems and provide actionable insights for stakeholders. While significant progress has been made in understanding the potential of the CBE and palm-cattle integration, addressing the identified research gaps is crucial for advancing sustainable agricultural practices. This study aims to contribute to this effort by employing system dynamics analysis to address cattle feed shortages using a CBE model.

## MATERIAL AND METHODS

**Research site and data collection.** Indonesia is the world's leading palm oil producer, with Riau Province having the largest area for oil palm plantations. Notably, this area generates significant palm oil by-products. Focusing the study on Riau Province enables the study of the CBE model in a region with a high feedstock concentration. Within Riau Province, Rokan Hulu Regency was chosen for further investigation based on its reported implementation of CBE principles. Thus, studying the model in Rokan Hulu enables us to leverage existing practices and potentially build upon them by identifying opportunities to integrate palm oil by-products into the local CBE framework. This focused approach facilitates an in-depth exploration of the CBE model to be adopted on a broader scale.

To create the model parameters, this study used cross-sectional data. Data collection began by identifying key variables to build the model using a system dynamics approach. The key variables and quantitative data were obtained through a combination of interviews and focus group discussions (FGDs). A total of 61 farmers were interviewed from August to December 2023 in Bono Tapung Village, Tandun Sub-district, Rokan Hulu Regency, Riau Province (Figure 1). The interviews focused on gathering detailed information about the availability and utilisation of palm oil by-products as cattle feed, the use of biomass feed as fibre and energy sources, feed price, and existing cattle carrying capacity based on feed. Farmers were selected using purposive sampling. The sample selection criteria were as follows: (*i*) active involvement in cattle farming and oil palm plantations; and (*ii*) experience in integrating palm oil by-products into cattle feed. The interviews were semi-structured, thereby allowing flexibility to explore additional insights to construct the CBE model.

Two FGDs were held to validate and expand upon the information gathered during the interviews. FGD participants included farmers and planters, management representatives from PTPN V (State-Owned Plantation Company V), province- and regency-level government officials, and private-sector and association stakeholders involved in palm oil and PKC production in Riau Province. The FGD aimed to identify challenges and opportunities for integrating palm oil by-products into a CBE framework. Discussions were guided by a moderator using a structured questionnaire to ensure comprehensive coverage of the CBE model. This mixed-method approach ensured robust and replicable data collection.

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Figure 1. Research sites for studying the potential of palm oil by-products

Source: modified from Google maps

Based on the initial data obtained, data were verified and validated. Verified data were then input into the stock and flow diagram. Model refinement and development were performed iteratively until a model depicting the actual conditions was obtained at the research site (Sterman 2000).

**CBE model framework.** The palm oil industry CBE model demonstrates a highly effective approach to achieving zero waste and sustainable agriculture. Applying a CBE model by integrating palm oil production with cattle farming (Figure 2) offers an effective approach to achieving zero waste. During palm oil production, by-products such as PKC and solid decanter are typically considered waste. However, within a CBE framework, these by-products are recycled and repurposed into nutritious cattle feed. Their nutritional content makes palm oil by-products highly valuable as a feed source. Repurposing palm oil by-products not only helps manage agricultural waste but also supports and sustains the national cattle population.

Indonesia's cattle population also generates significant quantities of manure, which can be utilised through composting. The resulting compost fertiliser is rich in nutrients and serves a crucial role in enhancing soil nutrient levels, thereby improving the productivity of oil palm plantations. Using compost fertiliser

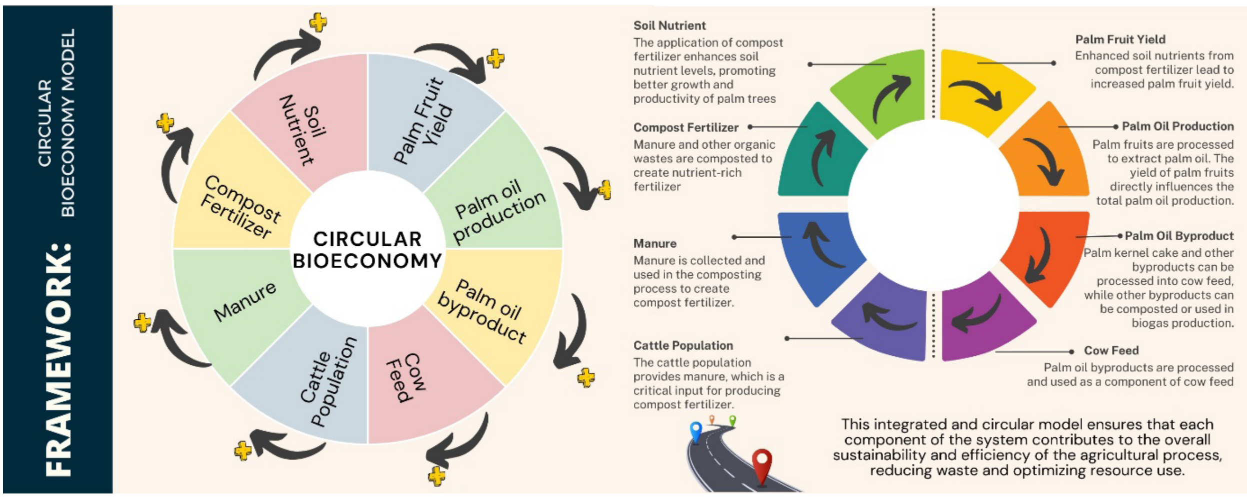


Figure 2. Circural bioeconomy model framework

Source: Author's own elaboration, building upon the findings of Swastika et al. (2024)

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also effectively substitutes for chemical fertilisers, significantly reducing operational costs. This substitution not only promotes environmental sustainability by mitigating the harmful effects of chemical fertilisers but also provides a cost-effective solution for farmers. Additionally, enhanced soil health leads to a significant rise in palm fruit yield, ensuring an increase in FFB productivity. This increased yield can result in higher production – a critical economic driver in many agricultural sectors. The palm oil extraction process generates by-products that include PKC and solid decanter, which are processed and converted into nutritious cattle feed.

This interconnected cycle ensures that all system components contribute to the overall efficiency and sustainability of the CBE model. By continuously recycling organic materials and minimising waste, the integrated model represents the principles of a CBE. This approach not only optimises resource use but also promotes environmental sustainability by reducing the need for external inputs and waste mitigation.

The framework (Figure 2) represents the authors' original contribution, developed by extending and adapting insights from a prior study by (Swastika et al. 2024). The study provided foundational concepts for integrating agricultural by-products within a circular bioeconomic model. Building upon these findings, the authors created a framework specifically for the palm oil industry, addressing its challenges and opportunities to address cow feed shortages through the CBE model approach.

**Study limitations.** The limitations of this study largely relate to modelling a CBE to specifically address the feed shortage in beef cattle farming. In this study, the focus is on exploring the integration of oil palm by-products into cattle feed, rather than comprehensively examining the entire CBE model. The research specifically investigates how these by-products can be effectively utilised to mitigate feed shortages in beef cattle farming. Therefore, while the study acknowledges the broader CBE concept, its scope is limited to evaluating the practical application and benefits of incorporating oil palm by-products into cattle feed systems.

**Defining the system boundaries.** This study defines the system boundaries for an integrated palm oil production and cattle farming system. Defining system boundaries is crucial for understanding the scope and limitations of the model, thereby ensuring that all relevant components and interactions are included whilst excluding irrelevant factors. The model design used in this study adopted the theory of CE, emphasising the concept of zero waste (Franco 2019; Gao et al. 2020; Guzzo et al. 2022).

Moreover, the model captures the potential utilisation of oil palm by-products by using oil palm frond (OPF) as a fibre source in cattle feed. Additionally, processing results from a palm oil mill yield several by-products that can be used as an energy source in cattle feed, such as PKC and solid decanter. In this model, each feed is converted from fresh material to a dry matter (DM)

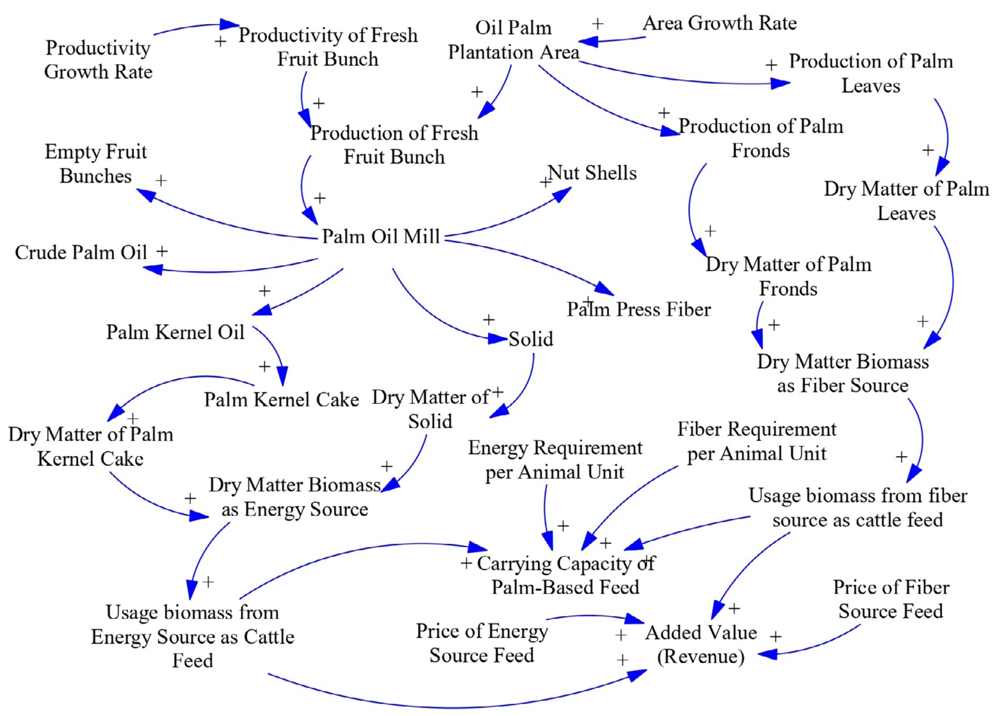


Figure 3. Causal loop diagram of potential palm oil by-products in the circular bioeconomy

Source: Author's own elaboration

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base to determine the conditions of beef cattle carrying capacity and its added value. A causal loop diagram of the potential palm oil by-products pursued in the CBE is created to provide an overview of the model established in this research (Figure 3). Furthermore, using Powersim Studio 10 (Powersim Software, Norway), the model was developed into a stock and flow diagram consisting of all variables used in this study.

The primary purpose of the model is to create a sustainable CBE system that maximises resource efficiency and minimises waste. By integrating palm oil production with cattle farming, the model aims to utilise by-products from each sector as inputs for the other. By clearly defining the system boundaries, this study ensures that the model remains focused and relevant to the objectives of creating a sustainable CBE for palm oil and cattle integration. This structural clarity allows for a more accurate analysis of the interactions and dynamics within the system.

**Equations and parameters.** The equations and parameters in this study were used to model the integrated palm oil and cattle farming system within the CBE framework. The model includes the stock change equations, auxiliary equations and constant parameters essential for simulating system dynamics and interactions (Sterman 2000). The stocks of FFB and plantation area were divided into three distinct areas: A, B and C. This segmentation is justified by the variations in plantation size, tree density and processing facility distribution to ensure that the model accurately represents the production dynamics and resource utilisation within the CBE model. All areas include crude palm oil processing plants, while area A specifically contains processing plants that produce palm kernel oil, with PKC as a by-product. The characteristics of the oil palm mills in Areas A, B and C are presented in Table 2.

The stock variables were calculated using the following equations:

FFB stock for Area 'A'

$$\text{FFB stock area 'A'}(t) = \text{FFB stock area 'A'}(t_0) + \int_{t_0}^{t} (\text{productivity rate }(s)\text{ area 'A'}) \tag{1}$$

FFB stock for Area 'B'

$$\text{FFB stock area 'B'}(t) = \text{FFB stock area 'B'}(t_0) + \int_{t_0}^{t} (\text{productivity rate }(s)\text{ area 'B'}) \tag{2}$$

FFB stock for Area 'C'

$$\text{FFB stock area 'C'}(t) = \text{FFB stock area 'C'}(t_0) + \int_{t_0}^{t} (\text{productivity rate }(s)\text{ area 'C'}) \tag{3}$$

Plantation area for Area 'A'

$$\text{Plantation area 'A'}(t) = \text{plantation area 'A'}(t_0) + \int_{t_0}^{t} (\text{new planting rate }(s)\text{ area 'A'}) \tag{4}$$

Plantation area for Area 'B'

$$\text{Plantation area 'B'}(t) = \text{plantation area 'B'}(t_0) + \int_{t_0}^{t} (\text{new planting rate }(s)\text{ area 'B'}) \tag{5}$$

Table 2. Oil palm mill characteristics of research sites (2023)

| Description | Oil palm mill – areas A | Oil palm mill – areas B | Oil palm mill – areas C |
|---|---|---|---|
| Plantation area (ha) | 7 593 | 3 080 | 6 394 |
| Number of trees (trees/ha) | 126 | 139 | 129 |
| Crude palm oil (CPO) production (tonnes/year) | 44 099 | 19 922 | 33 057 |
| Palm kernel oil (PKO) production (tonnes/year) | 47 362 | – | – |
| Palm kernel cake (PKC) production (tonnes/year) | 64 323 | – | – |
| Solid production (tonnes/year) | 4 725 | 2 131 | 3 668 |
| Processing facilities | CPO and PKO | CPO | CPO |

Source: Author's own elaboration building upon focus group discussion with PTPN V – Perseroan Terbatas Perkebunan Nusantara V. The fifth PT Perkebunan Nusantara (PTPN) is a state-owned plantation holding company that manages commodities such as palm oil, rubber, tea, and coffee. It is now organized into several sub-holdings, including PalmCo for palm oil and SupportingCo for supporting assets, under Holding Perkebunan Nusantara.

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Plantation area for Area 'C'

$$\text{Plantation area 'C'}(t) = \text{plantation area 'C'}(t_0) + \int_{t_0}^{t} (\text{new planting rate } (s) \text{ area 'C'}) \quad (6)$$

where: FFB stock area A/B/C ($t_0$) – the initial FFB stock in area A/B/C at time $t_0$; productivity rate ($s$) for area A/B/C – the rate at which FFB is produced in area A/B/C over time $s$; plantation area A/B/C ($t_0$) – the initial plantation area A/B/C at time $t_0$; new planting rate ($s$) – the rate at which new plantations are established in area A/B/C over time $s$.

To support the stock equations, several auxiliary equations were used to model additional aspects of the system. The auxiliary equations use the following equations:

FFB production:

$$\text{FFB production} = \text{plantation area} \times \text{productivity rate} \quad (7)$$

Total FFB production:

$$\text{Total FFB Production} = \text{FFB production area 'A'} + \text{area 'B'} + \text{area 'C'} \quad (8)$$

Palm kernel cake (dry matter):

$$\text{Palm kernel cake}(\text{DM}) = 0.035 \times \text{FFB processed in the palm oil mill} \quad (9)$$

Solid decanter (dry matter):

$$\text{Solid decanter}(\text{DM}) = 0.029 \times \text{FFB processed in the palm oil mill} \quad (10)$$

Oil palm fronds (dry matter):

$$\text{Oil palm fronds}(\text{DM}) = 0.2607 \times \text{oil palm plantation area} \quad (11)$$

Palm leaves (dry matter):

$$\text{Palm leaves}(\text{DM}) = 0.4618 \times \text{oil palm plantation area} \quad (12)$$

Cattle carrying capacity:

$$\text{Cattle carrying capacity} = \left(\frac{\text{DM fibre availability}}{\text{DM fibre requirement per AU}}\right) + \left(\frac{\text{DM energy availability}}{\text{DM energy requirement per AU}}\right) \quad (13)$$

Added value (revenue):

$$\text{Added value} = (Q_{PKC} \times P_{PKC}) + (Q_{Solid} \times P_{Solid}) + (Q_{OPF} \times P_{OPF}) \quad (14)$$

These auxiliary equations assist in understanding the overall system dynamics by connecting different components. By integrating these stock and auxiliary equations, the model provides a detailed and dynamic representation of the CBE system for palm oil and cattle integration.

**Conversion of materials to DM for model development.** In this study, all materials were converted to the DM form to ensure consistent model development. A proximate analysis was conducted to determine the DM content of the feed ingredients (OPF, solid decanter and PKC) according to Association of Official Analytical Chemists (AOAC) method

The OPF was sourced from an oil palm plantation. Two branches, including leaves and petioles, were chopped and thoroughly mixed. Approximately 1 kg of the mixture was taken and dried in an oven at 60 °C for 48 h to obtain a constant weight. The solid decanter was obtained from an oil palm processing factory. A 5 kg sample was mixed, and a sub-sample of approximately 1 kg was taken and dried in an oven at 60 °C for 48 h or until it reached a constant weight. PKC was obtained from an oil palm kernel factory and was already in a dry form. The proximate analysis results (Table 3) were used in the model to accurately represent the quantity and quality of feed ingredients. By converting all materials to their DM form, the model could more precisely simulate the interactions and efficiencies within the CBE framework.

**Model validation.** Model validation was conducted using an approach involving structural and output validity tests (Sterman 2000). Structural validity testing was performed through FGD activities involving relevant experts in Rokan Hulu Regency. The model's structure was refined based on recommendations from expert suggestions, field survey results, and literature study findings. The experts consulted included (*i*) academic experts from IPB University and State Islamic University (UIN) Suska Riau, (*ii*) oil palm industry practitioners from the management of PTPN V, and (*iii*) government officials from the Department of Animal Husbandry and Animal Health of Riau Province, the Department of Plantations of Riau Province, and the Department of Animal Husbandry and Plantations of Rokan Hulu Regency.

Table 3. Dry matter (DM) content of oil palm by-products

| Ingredients | DM (%) |
|---|---|
| PKC | 92.6 |
| OPF | 46.6 |
| Solid decanter | 24.4 |

OPF – oil palm frond; PKC – palm kernel cake
Source: Author's own elaboration

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Each expert was selected based on their professional background and relevance to the study objectives. Their qualifications included advanced degrees in agricultural sciences, economics or modelling, as well as practical experience in their respective fields. Suggestions were collected during the FGD and individual consultations. Key recommendations, such as refining feedback loops, refining stock and flow diagrams and adjusting parameter values, were integrated into the model following a thorough discussion and validation.

Regarding output validity testing, the mean absolute percentage error (MAPE) approach was employed. A small MAPE value indicates that the model is closer to actual conditions. The MAPE formula is presented as follows (Sterman 2000):

$$MAPE = \frac{1}{n}\sum_{t=1}^{n}\left(\frac{\left|Y_t - \overline{Y_t}\right|}{Y_t}\right) \times 100 \tag{15}$$

where: $Y_t$ – actual data values; $\overline{Y_t}$ – model simulation values; $n$ – year/time interval.

## RESULTS AND DISCUSSION

**Potential by-products of oil palm plantations for feed and carrying capacity.** The results indicate that the oil palm plantation area in Area 'A' increased steadily from 7 623.37 ha in 2024 to 7 808.17 ha in 2030. The oil palm plantation area in Area 'B' gradually increased from 3 085.14 ha in 2024 to 3 116.19 ha in 2030. Furthermore, the oil palm plantation area in Area 'C' experienced growth from 6 495.29 ha in 2024 to 7 140.10 ha in 2030 (Figure 4). All three areas should experience increased oil palm plantation coverage and corresponding production of FFB, palm fronds and palm leaves from 2024 to 2030. The trends indicate positive development and productivity in the oil palm plantations over the studied period.

The results reveal that the total FFB production is predicted to increase steadily from 60 261 tonnes in 2024 to 63 571 tonnes in 2030. PKC also showed a continuous predicted increase in a DM basis, rising from 2 109 tonnes in 2024 to 2 225 tonnes in 2030 with a growth of 0.89% per year (Table 4). Solid decanter and OPF (DM) also exhibit a positive predicted trend. Solid decanter should also increase from 1 748 tonnes in 2024 to 1 844 tonnes in 2030, and palm fronds and leaves should rise from 50 531 tonnes in 2024 to 53 059 tonnes in 2030 (growth 0.81% per year). The continuous predicted increase in fresh weight production of FFB and PKC, solid decanter and OPF on a DM basis highlights the expected growth and sustainability of palm oil biomass resources over the specified period.

The use of OPF alone will not achieve good performance since it is a good source of fibre but lacks certain nutrients essential for cattle, such as protein, vitamins and minerals (Zahari et al. 2003; Rusli et al. 2021). Thus, other feed sources must be supplemented to create a balanced feed. PKC and solid decanter are recommended since they are rich in protein, which is essential for cattle growth and development (Warly et al. 2015; Abdeltawab and Khattab 2018; Rusli et al. 2021). Additionally, these by-products provide a good energy source that can contribute to the improved weight gain and overall health of the animals. These palm oil by-products can be valuable resources that make it a sustainable and cost-effective solution.

System dynamics modelling employs the MAPE approach as a metric to assess the accuracy of predictions against actual values. The data on oil palm plantation areas in the study spanning the 2017–2021

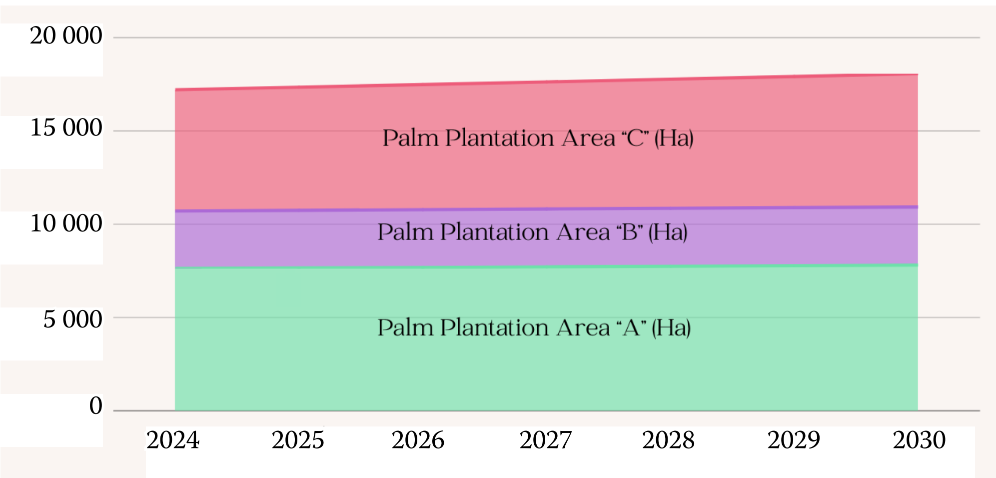


Figure 4. Potential of oil palm plantation area in research sites
Source: Author's own elaboration

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Table 4. Potential of oil palm by-products based on fresh and dry matter weights

| Oil palm plantation | Year | | | | | | |
|---|---|---|---|---|---|---|---|
| | 2024 | 2025 | 2026 | 2027 | 2028 | 2029 | 2030 |
| Fresh weight (tonnes) | | | | | | | |
| Fresh fruit bunches | 60 261 | 60 796 | 61 338 | 61 886 | 62 441 | 63 002 | 63 571 |
| Palm fronds | 172 038 | 173 427 | 174 834 | 176 259 | 177 702 | 179 164 | 180 645 |
| Palm leaves | 12 301 | 12 400 | 12 501 | 12 603 | 12 706 | 12 810 | 12 916 |
| Dry matter (tonnes) | | | | | | | |
| Palm kernel cake | 2 109 | 2 128 | 2 147 | 2 166 | 2 185 | 2 205 | 2 225 |
| Solid decanter | 1 748 | 1 763 | 1 779 | 1 795 | 1 811 | 1 827 | 1 844 |
| Palm fronds and leaves | 50 531 | 50 939 | 51 352 | 51 771 | 52 194 | 52 624 | 53 059 |

Source: Author's own elaboration

period was used to validate the model. Validation results, assessed through MAPE values for land area, demonstrate that oil palm plantations areas 'A' and 'C' exhibit MAPE values of 4.80% and 2.57%, respectively (MAPE < 5%), indicating the system dynamics model's high accuracy in predicting the oil palm plantation land area. The area of oil palm plantation 'B', with a MAPE value of 5.23% or < 10%, also signifies an acceptable level of accuracy in land area prediction. These findings underscore the model's proficiency in capturing patterns and trends within the modelled system, thereby delivering precise predictions.

Table 5 presents the potential use of oil palm by-products in animal feed rations on a DM basis as fibre and energy sources in the baseline simulation. Based on the production of OPF and leaves of 5 872 tonnes DM/ha, PKC production of 35 kg DM/tonne FFB, and a solid decanter of 29 kg DM/tonne FFB (Priyanti et al. 2024), the availability of feed from oil palm industry biomass was calculated. On a DM basis, OPF and leaves contribute to the biomass's fibre source, which is predicted to increase steadily by 0.73% per year, from 20 212.32 tonnes in 2024 to 21 223.48 tonnes in 2030. On the other hand, PKC and solid decanter contribute to the biomass's energy source, which is predicted to gradually increase by 0.8% per year, from 992.20 tonnes in 2024 to 1 046.70 tonnes in 2030. The total animal feed – as the sum of total fibre and energy source – increased from 21 204.52 tonnes in 2024 to 22 270.18 tonnes in 2030, equal to an increase of 0.8% per year. Based on the results, the data suggest a positive trend in the potential use of oil palm industry by-products in animal feed rations, indicating the availability of these by-products for animal feed. Increasing the potential use of oil palm by-products that consist of OPF, palm leaves, PKC and solid decanter will yield an increase in total animal feed on a DM basis.

Table 5. Potential use of oil palm by-products as fibre and energy sources for animal feed

| Year | Fibre source of oil palm plantation by-products (DM) | | | Energy source of palm oil mill by-products (DM) | | | Total animal feed (DM, tonnes) |
|---|---|---|---|---|---|---|---|
| | palm fronds (tonnes) | palm leaves (tonnes) | total fibre source (tonnes) | palm kernel cake (tonnes) | solid decanter (tonnes) | total energy source (tonnes) | |
| 2024 | 17 940.13 | 2 272.19 | 20 212.32 | 843.66 | 148.54 | 992.20 | 21 204.52 |
| 2025 | 18 084.99 | 2 290.54 | 20 375.53 | 851.15 | 149.86 | 1 001.01 | 21 376.54 |
| 2026 | 18 231.71 | 2 309.12 | 20 540.83 | 858.72 | 151.20 | 1 009.92 | 21 550.75 |
| 2027 | 18 380.30 | 2 327.94 | 20 708.24 | 866.40 | 152.55 | 1 018.95 | 21 727.19 |
| 2028 | 18 530.80 | 2 347.00 | 20 877.80 | 874.17 | 153.92 | 1 028.08 | 21 905.88 |
| 2029 | 18 683.22 | 2 366.30 | 21 049.53 | 882.04 | 155.30 | 1 037.34 | 22 086.87 |
| 2030 | 18 837.62 | 2 385.86 | 21 223.48 | 890.00 | 156.70 | 1 046.70 | 22 270.18 |

DM – dry matter

Source: Author's own elaboration

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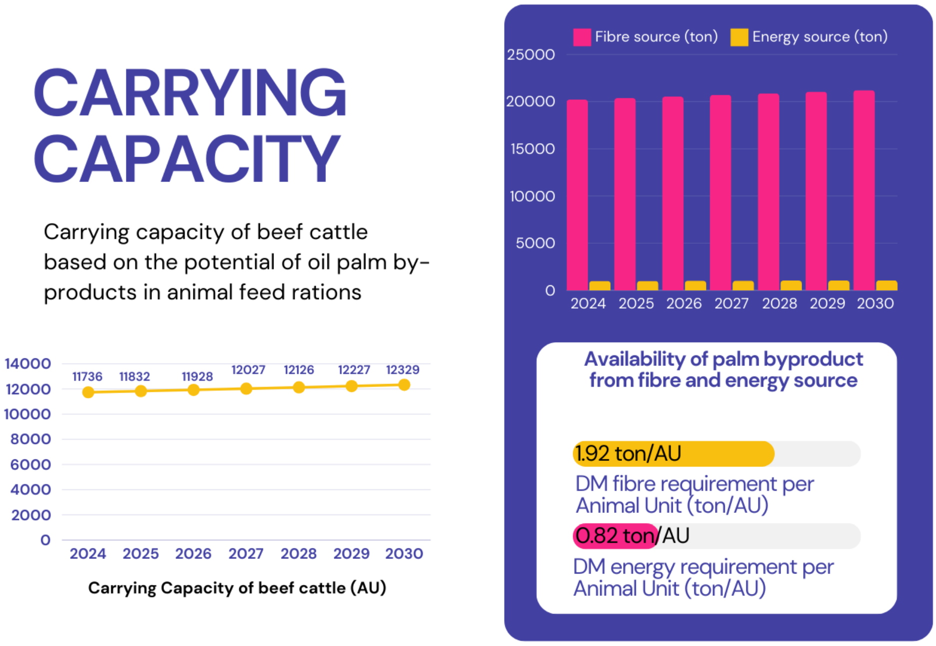


Figure 5. Carrying capacity of beef cattle based on the potential of oil palm by-products in animal feed rations

Source: Author's own elaboration

The fibre and energy sources from PKC and solid decanter on a DM basis requirement per animal unit (AU) remained constant at 1.92 and 0.82 tonnes, respectively. The results indicate that the carrying capacity of beef cattle should increase steadily over time, from 11 736 AU in 2024 to 12 329 AU in 2030 (growth: 0.82% per year) (Figure 5). The results indicate that the availability of oil palm by-products, both as a fibre source and an energy source, can support the carrying capacity of beef cattle. The projected increase in carrying capacity over time highlights the potential for utilising oil palm by-products to enhance the efficiency of beef cattle farming, thereby contributing to overall sustainability.

Over the 2024–2030 period, a consistent increase in the carrying capacity is expected, reflecting the potential of oil palm by-products to support beef cattle production. This aligns with previous research indicating the viability of utilising oil palm by-products as feed resources for beef cattle (Abdeltawab and Khattab 2018; Ghani et al. 2017; Azmi et al. 2019; Priyanti et al. 2024). The increasing availability of oil palm by-products as both fibre and energy sources underscores their importance in enhancing beef self-sufficiency and palm oil sustainability in Indonesia. Such findings are crucial, especially considering the increased demand and limited cattle feed resources in beef cattle production areas (Agus and Widi 2018).

The requirements of 1.92 tonnes of fibre and 0.82 tonnes of energy from PKC and solid decanter per AU emphasise the significance of balanced nutrition in achieving the observed carrying capacities of beef cattle. Ensuring proper fibre and energy levels in feed formulations is essential for promoting optimal beef and dairy cattle performance (Zahari et al. 2003). Furthermore, using oil palm by-products in animal feed formulations presents opportunities for enhancing the CBE within the agricultural sector. Notably, oil palm producers can mitigate waste generation and reduce environmental impacts by incorporating oil palm by-products into livestock diets since previous studies have highlighted the effectiveness of such palm-cattle integration (Chang et al. 2020; Grinnell et al. 2022). Continued research and innovation in this area can further optimise the development of more resilient and environmentally sustainable livestock production systems.

**Value-added estimation of using oil palm by-products as feed.** The utilisation of unused waste from both oil palm plantations and palm oil mills as cattle feed increases the economic value of such waste, which can provide additional income for the palm oil industry. According to Sura and Ardi (2023), by-products from palm oil mills still have economic value due to the ability to convert such waste into beneficial products. For instance, PKC can be reprocessed as feed to significantly increase the performance of animals, weight gain, production and the coefficient of digestibility whilst also addressing increasing feed prices (Abdeltawab and Khattab 2018). Considering the transportation and labour costs involved in collecting these by-products, their economic value is estimated at approximately USD 3.09 per tonne for OPF, USD 80.30 per tonne

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for PKC and USD 6.18- per tonne for solid decanter. Based on these economic value assumptions, using these oil palm by-products as cattle feed can provide an additional value of up to USD 333 000 under existing conditions (Table 6). Ardiani et al. (2023) reported that selling OPF (only the sticks) can increase community income by USD 8.78–14.66 per month. Notably, this revenue is higher than the revenue for utilising OPF as cattle feed. However, using OPF as cattle feed in this study also alleviates environmental issues.

In line with the expected increase in oil palm plantation areas at the three research sites over the 2024–2030 period, the number of by-products used as cattle feed will also increase. This will impact the increase in potential revenue obtained from the increased value added to those by-products. As shown in Table 6, the total added value of the three by-product types will increase by approximately 5.99%, from USD 317 000 to USD 333 000 by 2030 (approximately 0.86% annually). An increase of 6.43% or 0.92% per year is also expected in the added value of PKC – higher than the added value increase of OPF, which is estimated at 6.43% or 0.92% per year despite it being used in the same proportion in cattle feed. This is because the economic value of the PKC is higher than that of OPF, with differences in DM content as well.

This finding indicates that implementing a CBE in the oil palm industry through utilising by-products as animal feed can potentially result in new profit sources and reduce the cost of processing or managing by-products. This result supports the research of Sura and Ardi (2023), which revealed that the driving factor in applying a CBE in the oil palm industry is the potential benefit of the CBE itself through increased income and new revenue sources (in this case, from reprocessing by-products as cattle feed) as well as cost reduction (in this case, the cost of managing waste). Moreover, additional revenue from the use of oil palm waste for animal feed, which is relatively high, is very promising and should improve the sustainability of the palm oil industry and feed sources for other businesses (e.g. livestock). Cheah et al. (2023) suggested that a CBE for income generation has the potential to deal with abundant waste from the palm oil industry.

The palm oil industry's shift towards a CBE approach to addressing livestock feed shortages underscores the importance of resource efficiency, with a focus on the repurposing of agricultural by-products to provide sustainable alternatives to conventional feed sources. The palm oil industry generates significant by-products, such as POME and PKC, which can be repurposed as animal feed (Hanum 2023; Siagian et al. 2024). According to Cheah et al. (2023), utilising palm oil waste for cattle feed can lower production costs and reduce dependency on imported feed, thereby enhancing local economic stability.

The adoption of CBE practices within the palm oil industry also has positive spillover effects on local economies. For instance, processing palm oil by-products into cattle feed can create jobs in the rural areas where palm oil plantations are often located. This could reduce unemployment and contribute to economic resilience in these communities. According to Yusuf and Ojedokun (2024), the transition to a CBE enables the efficient utilisation of renewable resources and the recovery of valuable materials from waste, which economically stimulates job opportunities in bio-based sectors – particularly in waste valorisation and biomass production. By integrating bio-based innovations, the palm oil industry can contribute to national GDP

Table 6. Potential added value from the use of palm by-products in animal feed rations

| Year | OPF | | PKC | | Solid decanter | | Total added value (USD*) |
|---|---|---|---|---|---|---|---|
| | volume (tonnes) | added value (USD*) | volume (tonnes) | added value (USD*) | volume (tonnes) | added value (USD*) | |
| 2024 | 20 212.32 | 239 440.83 | 843.66 | 73 767.82 | 148.54 | 3 811.49 | 317 020.14 |
| 2025 | 20 375.53 | 241 374.31 | 851.15 | 74 422.61 | 149.86 | 3 845.27 | 319 642.12 |
| 2026 | 20 540.83 | 243 332.49 | 858.72 | 75 084.99 | 151.20 | 3 879.56 | 322 297.04 |
| 2027 | 20 708.24 | 245 315.69 | 866.40 | 75 756.21 | 152.55 | 3 914.21 | 324 986.04 |
| 2028 | 20 877.80 | 247 324.27 | 874.17 | 76 435.39 | 153.92 | 3 949.29 | 327 709.02 |
| 2029 | 21 049.53 | 249 358.68 | 882.04 | 77 123.35 | 155.30 | 3 984.81 | 330 466.89 |
| 2030 | 21 223.48 | 251 419.33 | 890.00 | 77 819.70 | 156.70 | 4 020.82 | 333 259.85 |

*1 USD = IDR 16 190

OPF – oil palm frond; PKC – palm kernel cake

Source: Author's own elaboration

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through the production of high-value-added products such as animal feed (Taron and Gebrezgabher 2024). Additionally, the valorisation of waste into high-value cattle feed contributes to income generation for farmers through the sale of processed feed (Cheah et al. 2023).

**CBE analysis of using oil palm by-products for animal feed.** The CE analysis was performed using the 10 R-strategies frameworks, which refers to how circular design and manufacturing may keep resources in use. R-strategies are a valuable tool for visualising and understanding the different stages of resource use in a CE. Morseletto (2020) outlined the three groups of targets in the framework: (*i*) smarter product manufacturing and use, (*ii*) extended lifespans of products and their parts, and (*iii*) the useful application of materials. The target of smarter product manufacturing and use includes the strategies of refuse (R0), rethink (R1) and reduce (R2). This target describes making a product redundant by offering the same function with a different product. The target intends to make product use more intensive and increase efficiency in product manufacturing or use by consuming fewer natural resources.

The target on the extended lifespan of products and their parts includes the strategies of reuse (R3), repair (R4), refurbish (R5), remanufacture (R6) and repurpose (R7). This target accommodates the reuse of a discarded product – that remains in good condition and fulfils its original function – by another consumer, as well as the repair and maintenance of a defective product so that it can be used for its original function. The target may also restore an old product, bring it up to date, and use parts of discarded products in a new product for the same function. The target related to the useful application of materials includes the strategies of recycling (R8) and recovery (R9). This target includes processing materials to obtain the same (high grade) or lower (low grade) quality and the incineration of material with energy recovery.

The use of oil palm by-products as animal feed showed that the design supports a CBE through several strategies:

*i*) Smarter product manufacturing and use

Using oil palm by-products as an animal feed model applies the 'rethink' (R0) and 'reduce' (R2) strategies, where there is a material exchange between oil palm by-products to produce animal feed. This is achieved by implementing a closed-loop production system that allows materials to be used intensively for as long as possible in the production cycle. The 'reduce' strategy implements using oil palm by-products as raw materials, which can reduce the extraction of natural resources for animal feed.

*ii*) Extending the lifespan of the product and its parts

Using oil palm by-products as an animal feed model applies the 'reuse' (R3) and 'repurpose' (R7) strategies by using oil palm by-products that would otherwise be discarded in oil palm plantations and become waste in the environment. The valorisation of new products, such as animal feed, will add value for oil palm companies. The 'repurpose' (R7) strategy has also been implemented by processing oil palm by-products into animal feed.

Usapein et al. (2022) have reported that utilising oil palm by-products as animal feed demonstrates support for a CBE through the 10 R-strategies frameworks. Focusing on optimising the potential of oil palm by-products will align with the principles of a CBE and sustainable resource management. By repurposing oil palm fronds into animal feed ingredients, the palm oil industry may enhance its sustainability and contribute to cost reduction in production processes (Cheah et al. 2023). Furthermore, the palm oil industry's shift towards a CBE approach emphasises resource efficiency and by-product minimisation, aiming to lower production costs through the reuse and recycling of biomass by-products.

## CONCLUSION

The CBE model, which is based on the recovery of waste and by-products from the palm oil transformation process, facilitates the estimation of potential cattle feed production. By repurposing by-products such as OPF, PKC and solid decanter, a total of 21 204.52 tonnes of animal feed can be produced to create an annual revenue of USD 317 020.14. This strategy can also supplement animal diets with nutritious and high-fibre sources whilst promoting CBE practices and reducing reliance on conventional feed sources. Overall, the strategic integration of oil palm by-products into animal feed formulations holds great potential as a sustainable and holistic approach to agricultural practices.

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