Circular Economy Rebound Effect in the Food Sector: an Agent-based Model

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Abstract: Food waste represents a significant challenge for the food sector, and circular economy practices can reduce the negative sustainability impacts of food waste. Nevertheless, the Circular Economy Rebound (CER) effect may diminish the effectiveness of circular practices. To explore CER in the food sector and the circumstances that trigger it, this study develops an agent-based model simulating consumer behavior in response to circular economy strategies. This method provides valuable insights into the potential impacts of circular initiatives, also offering guidance for companies aiming to adopt circular economy practices effectively.

Keywords: Agent-based modelling; circular economy rebound; food sector; food waste; circular economy; rebound effect; simulation

1. INTRODUCTION AND BACKGROUND

The food sector, with a global market estimated at $9.1 trillion annually, is one of the largest consumer goods systems (Statista, 2024). In this industry, one of the major challenges is food waste, as nearly 1/3 of food produced worldwide is wasted each year, causing environmental, social, and economic impacts (FAO, 2019). Circular economy (CE) principles offer solutions for preventing and managing food waste through practices such as advanced shelf-life monitoring, discounts on near-expiration products, and reprocessing food for human consumption or other uses such as animal feed, composting, or energy recovery (Grewal et al., 2024). These CE practices can recover value from food waste, alleviating its negative impacts on sustainability. However, CE practices may have unintended consequences, such as the circular economy rebound (CER) effect, where increased efficiency lowers per-unit impacts but leads to greater overall consumption, offsetting sustainability benefits (Zink and Geyer, 2017). Rooted in the rebound effect from energy studies (Jevons, 1866), CER highlights how circular initiatives can lead to increased sustainability but may, paradoxically, also increase consumption, either directly through increased product use or indirectly by reallocating efficiency savings to other resource-intensive goods. (Metic and Pigosso, 2022; Zink and Geyer, 2017). The principles of CER are relevant to the food sector, where CE strategies such as reprocessing, despite reducing waste and improving efficiency and sustainability, may unintentionally trigger CER mechanisms (Lowe et al., 2024; Maier et al., 2023). As CE is theorized to reduce resource consumption, CER should be thoroughly understood to develop strategies that truly mitigate environmental impacts. Although CER has been analyzed in the literature, studies are predominantly general or conceptual, with a notable lack of comprehensive, quantitative investigations (Lowe et al., 2024; Castro et al., 2022). In particular, no empirical studies fully address CER in the food sector, highlighting the need for measurable approaches to complement existing qualitative insights and accurately estimate CER dynamics (Zhang et al., 2022). The ex-ante assessment of CER is crucial for preventing rebounds, despite being marginally discussed in the literature (Metic and Pigosso, 2022). To bridge this gap, this study aims to investigate the possible emergence of CER in the food sector by developing an agent-based meta-model. Agent-based modelling (ABM) appears as a promising but not yet utilized tool for the ex-ante estimation of CER (Lowe et al., 2024). By focusing on CE strategies for preventing and recovering near-expiration food, the model analyzes the direct rebound effect generated by the price/income mechanism (Metic and Pigosso, 2022). This mechanism arises when improvements in production efficiency increase the demand for the same product due to lower prices. Moreover, the reduced costs free up income to buy more of that product, further stimulating supply (Metic and Pigosso, 2022). The simulation of a food system involving food producers and consumers allows for studying the possible emergence of CER in this context, answering the following research questions. RQ1: "*How can the circular economy rebound effect be modelled in the food sector?*", RQ2:"*Under which circumstances can the circular economy rebound effect occur in the food sector?*". Moreover, employing simulation models to address these questions can provide methodological contributions also in other fields, such as the use of computational methods for studying social systems.

2. METHODS

2.1 Meta-model description

Typically, a model is designed to represent a specific system. However, in this case, the approach differs as the framework presented is a **meta-model**. A meta-model serves as a higher-level abstraction that can be adapted to develop various specific models. This characteristic is particularly valuable, as it leverages the isomorphisms shared by many production and distribution systems that operate in a retail context and involve a final consumer, often exhibiting rebound effects. Rather than representing the distribution system of a particular good, the meta-model defines a generic structure that becomes specialized during the model specification phase, transitioning from the meta-model to a tailored model for the system under analysis. The proposed meta-model encompasses **three types of entities**: two agents, namely consumers and companies (the latter integrating both manufacturers and retailers), and one passive entity, the products. The model can also include several product classes, representing different product types, which can be stored by a company, can be sold to consumers, and can not be sold after a specific time range, for example, embodying clothes that go out of fashion or food products that expire. The time-step Δt is variable and can be adjusted based on the specific characteristics of the system being modeled. The **company agent** keeps a stock of products, subdivided into different classes. The agent keeps stock for each product class, which is initialized as the total market demand evenly split among all companies. At each t, companies forecast demand by utilizing a weighted average of recent sales and subsequently adjust production to meet projected demand while maintaining sufficient safety stocks to ensure product availability (Lewis, 2012). Periodically, companies evaluate their economic performance, considering both their absolute revenue and their position relative to competitors. Based on these evaluations, companies could decide whether to implement long-term sustainable strategies, such as enhancing the sustainability s_j and the quality q_j of a product j. This provides companies with a set of actuators on their environment (i.e., the market) suitable for our purposes, enabling the identification and observation of rebound effects. In the model, each **product object** represents a single product generated by a company, belonging to one of many predefined product classes and possessing attributes: quality (q_j), sustainability (s_j), price (p_j) and the remaining shelf life (rl_j) of the product relative to its shelf life (sl_j). Additionally, a target stock value tt_j is assigned, representing the quantity of the product that users want to keep. It was hypothesized that the production cost pc_j is not determined by the company but computed as a function of products' sustainability and quality, as described in Eq. 1:

$$pc_j = \eta \cdot (1 + \Omega \cdot q_j + \delta \cdot s_j) \tag{1}$$

During the setup phase, the attributes of primary products are initialized randomly within predefined intervals specified in the input data. Once on the market, products are subject to a dynamic ageing process, so that $rl_j(t+1) = rl_j(t) - 1$. If their residual life falls below a threshold, their price is reduced by a fixed percentage to incentivize purchase. If still unsold, the product undergoes reprocessing when its residual life reaches a second and higher threshold of the shelf life. This process transforms the product into a new class, extending its lifecycle and reducing waste in alignment with circular economy principles (Chiaraluce et al., 2021). Each product can undergo this reprocessing only once. The reprocessing strategy in the model is governed by a reprocessing matrix, which defines the possible transformations for expiring products. Each row of the matrix represents a class of products to be reprocessed, while the columns indicate the destination classes. Once reprocessed, the original product is removed from the system and replaced with a new product belonging to the destination class. The attributes of the new product are adjusted to reflect the characteristics of its final class. The production cost of the new product is recalculated, and the final price is then determined by adding a profit margin to the recalculated cost. Waste constitutes a specific category delineated for products that are not recoverable. The model does not include any specifications regarding the different types of waste, and includes a multiplier variable m that can increase the reprocessing efficiency, increasing the amount of reprocessed products put on the market while maintaining the proportions established for waste and reprocessed product. **Users** are agents that manage a stock of products, divided into different product classes. Each agent consumes a portion of their stock at every Δt based on individual and randomly assigned consumption rates, ensuring that the total consumption rate remains below a threshold. Following consumption, users evaluate whether to purchase new products. This decision is guided by a utility function (Eq. 2) that accounts for the characteristics of each product j. Each characteristic is weighted by each user i personal preferences (α_i, β_i, γ_i), and the utility function is normalized for each product to produce values between 0 and 1 and guarantee comparability. Users' preferences are sampled from the uniform random distribution between 0 and 1. To ensure model stability and compatibility with the utility function, the attributes of all products are normalized before being assessed, preventing disproportionate influences from attributes such as price, which could vary across product classes.

$$U_{ij} \propto (\alpha_i \cdot q_j + \beta_i \cdot s_j - \gamma_i \cdot p_j) \cdot \frac{rl_j}{sl_j} \tag{2}$$

Users compare all available products on the market and select the one that maximizes their utility. Once the product with the highest utility is identified, users decide whether to purchase it based on their current stock of similar products (st_i) relative to their target stock (t_i), and their purchasing propensity (pp_i). The decision rule is described in Eq. 3:

$$\frac{s_i}{t_i} \leq max(U_{ij}) \cdot pp_i \tag{3}$$

This mechanism reflects the users' inclination to buy a product, even when their stock levels approach the target, as long as the product's utility and the purchase trigger threshold justify the purchase.

Every modeling process involves constructing an abstraction of a system tailored to a specific purpose (Galán et al., 2009). Since this model represents purchasing behavior to assess the impact of near-expiration reprocessing, a metric for CER has to be characterized, to assess whenever it could be characterized as an emergent property (Bedau, 1997). Especially, CER could be approximated by the ratio of the change in purchases to the change in sustainability of all products in the system (Zink and Geyer, 2017). While the literature does not offer a precise formula for CER, it is conceptually linked to the rebound effect (RE), described as the improvements in energy efficiency that do not decrease energy use (Greening et al., 2000). In this context, it could be interpreted as improvements in sustainability leading to increased product consumption rather than its reduction:

$$CER(t) = \frac{\Delta pu(t)}{\Delta E[S(t)]} \tag{4}$$

where $pu(t)$ is the total number of purchases in the system at time t and $E[S(t)]$ is the average level of sustainability of all products in a given time step. So, $CER > 1$ indicates that the increase in sustainability corresponds to a more-than-proportional increase in purchasing behavior, highlighting the presence of a rebound effect. The higher $CER(t)$, the greater the rebound effect in the system.

2.2 Model specification

The model specification involves several activities to ensure the simulation accurately represents the dynamics of the rebound effect in a specific system. First, Δt must be defined in relation to the expiration period of the products under consideration, to align the temporal resolution of the model with the real-world product lifecycle. Second, it is necessary to identify the relevant product categories that significantly influence the system's behavior. Third, the reprocessing relationships among the identified product categories must be defined. This requires a thorough analysis of the reprocessing relationship matrix to understand how different categories interact. Finally, determining a reasonable number of customers and companies in the market is required. The selected market for the simulation is the mass-consumption food sector. This choice was driven by the relevance of food waste management through CE practices for sustainable development. Furthermore, the outcomes of qualitative interviews performed before the development of the model had facilitated the construction of a reasonable functional relationship matrix. The text of the interviews is available upon reasonable requests. The four core activities needed for specification generic meta-model depicted in previous section were executed as follows.

The Δt was set to one day. This choice reflects the daily expiration dynamics of fresh products, which were the focus of the model. Given the short average lifespan of fresh products, it was reasonable to assume that items reprocessed on a given day could be sold the following day. Relevant product categories were identified as fresh fruits and vegetables, frozen fish, fresh meat, processed meat, pasta, canned fish, and ready-to-eat meals. This selection aimed to balance sufficient completeness with clarity, prioritizing comprehensibility given that the paper also aims to present a methodological framework. While the model does not fully represent the entire food market, this subset of categories was deemed adequate for the study's objectives. A functional relationship matrix was constructed using the product categories and based on the mentioned

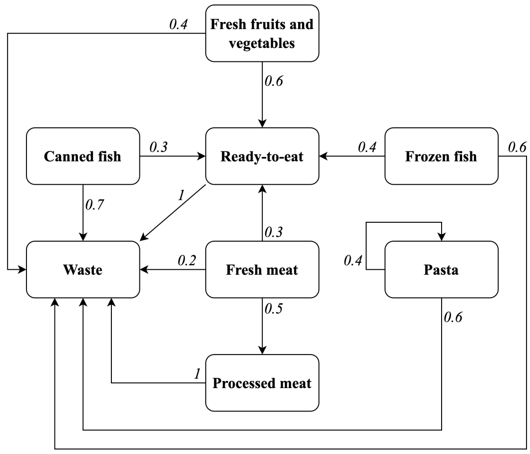

Fig. 1. Network representation of the reprocessing matrix

preliminary qualitative interviews (see Fig. 1). Although it represents a simplified and quantitative interpretation of qualitative phenomena, the goal was not to assess the impact of specific combinations on the rebound effect but rather to observe whether the effect emerged under given conditions. Finally, a reduced number of agents was used in the simulation. This choice was made because in preliminary analysis we observed a lack of impact of increasing agent numbers on the emergence of the rebound effect, still maintaining computational efficiency. Also, this instance of the meta-model was designed as a proof of concept rather than a detailed representation of a real system. The model was implemented using the NetLogo platform, chosen for its simplicity and suitability for conducting experiments without the need for extensive development. The experiments were set up using NetLogo's BehaviorSpace tool, which allows for systematic exploration of the relationship between model behavior and the parameters' space. While the specific experimental configurations are not detailed in this paper for brevity, the replicability of the analysis is ensured through open access to the model and associated experimental settings at this repository. Each simulation run lasted 700 time steps, as preliminary observations indicated that this duration was sufficient to allow the system to exit transient dynamics and reach a stable state. Accordingly, the analysis of the results focused exclusively on the final 200 time steps to ensure robust insights into the system's behavior. Given the stochastic nature of the model, each parameter combination was simulated 10 times for results' reliability.

3. RESULTS AND DISCUSSION

To explore the model, we opted to define and analyze specific scenarios tailored to address our research question. The difference in the observable variables between scenarios with and without reprocessing was calculated, given that in Eq. 4 CER is computed as a difference between two settings, along with the associated uncertainty. Further detail on the analyzed scenarios is provided below. The results of each scenario were then compared with those obtained in the baseline configuration without reprocessing, guaranteeing that the impact of the alterations implemented in each scenario is evaluated in relation to the established reference point. To statistically validate these differences, two-tailed t-tests were performed (considered statistical significant with $p < 0.05$). The relative uncertainty (i.e. standard deviation of the measured values) was employed to assess results robustness.

3.1 Scenario A

Table 1 summarizes the impact of introducing reprocessing at a baseline reprocessing rate (5 companies, 50 users, and users i buying inclination $pp_i = 2$). Results indicate a slight decrease in purchases ($\Delta = -0.022$), accompanied by improvements in the sustainability of purchased products ($\Delta = 0.050$). However, the high relative uncertainty and the lack of statistical significance for purchases ($p = 0.296$) suggests limited impact at this scale.

Table 1. Scenario A results.

Variable	Δ	Rel. Uncertainty (%)	p-value
P	-0.022	31.4	0.296
$E[S]$	0.050	13.1	0.001

Considering the low significance and high uncertainty of the results, it is not possible to draw conclusions. A possible reason may be the low percentage of reprocessed products with respect to the total products in the system. The number of reprocessed products makes the investigated dynamics of interest not clearly observable, as it may be insufficient to overcome the inherent noise of socioeconomic models (Wierzbicki, 1995).

3.2 Scenario Multiplier Sensitivity

An analysis was conducted to assess the effect of the multiplier m ranging from 1 to 10 to evaluate the impact of increasing the proportion of reprocessed products on the uncertainties of the analyzed variables. This scenario aimed to evaluate the system's sensitivity to a variation in reprocessing efficiency. Results are summarized in the following Table 3 and Table 4. The findings indicate that, with a multiplier of 3 (33.04% of products reprocessed), the relative uncertainty for all variables drops below 10%, and the p-values become highly statistically significant. Later values show consistent trends.

Table 2. Scenario multiplier sensitivity - P

Multiplier	1	2	3
Av. reproc. prod. %	7.33%	18.1%	33.04%
Δ	0.003	-0.153	-0.199
Rel. uncertainty	44.55%	14.90%	3.38%
p-value	0.91	0.001	0.000

Table 3. Scenario multiplier sensitivity - $E[S]$

Multiplier	1	2	3
Av. reproc. prod. %	7%	18.1%	33.04%
Δ	0.049	0.197	0.321
Rel. uncertainty	22.84%	5.62%	2.26%
p-value	0.004	0.000	0.000

The results of this scenario demonstrate that a higher reprocessing rate reduces uncertainty and enhances the reliability of the observed improvements in sustainability and decreases in purchases. Therefore, the following scenarios are formulated by maintaining the multiplier equal to 3 to ensure the results' significance.

3.3 Scenario A2

Scenario A2 applied the optimal multiplier identified in the previous analysis to assess system stability, distinguishing between primary and reprocessed purchases to explore consumer preferences. Applying a multiplier of 3 (33.04% reprocessing rate) produced highly reliable and statistically significant results, as shown in Table 4. Sustainability of purchased and all products improved ($\Delta = 0.289$ and 0.218, respectively), while purchases decreased significantly ($\Delta = -0.212$). The Rebound Effect (RE) was calculated as -0.97.

Table 4. Scenario A2 results.

Variable	Δ	Rel. Uncertainty (%)	p-value
P	-0.212	2.98	1.06×10^{-7}
$E[S]$	0.289	4.01	7.21×10^{-10}

The negative CER obtained in this scenario indicates an inverse rebound, as increased sustainability led to fewer overall purchases. Since primary products maintain a constant level of sustainability, the positive increase in sustainability of purchased products is only attributable to the purchased reprocessed products. This result suggests that consumers tend to substitute primary products with reprocessed ones, keeping the overall number of purchases stable. In this scenario, the average price of reprocessed products is higher than that of primary ones. This condition may appear contradictory, but it can be explained by considering that most reprocessed products belong to the ready-to-eat class (cf. Fig. 1), which is more expensive than other product types and consequently raises the average price. Price is a crucial element in the emergence of CER; therefore, the relevance of the pricing of reprocessed products is investigated in greater detail in the following scenario.

3.4 Scenario B

Scenario B, whose results are presented in Table 5, focused on comparing the prices of primary and reprocessed products disaggregated by product category, as global average prices often mask class-specific dynamics, to study the influence of pricing on CER. Focusing on ready-to-eat products, which represent the majority of reprocessed products, allowed observing how reprocessed ready-to-eat products were slightly cheaper than their primary counterparts ($\Delta = -0.696$, $p = 2.30 \times 10^{-6}$).

Table 5. Scenario B results.

Variable	**Value**
Av. price of Reprocessed ready-to-eat	21.5
Av. price of Primary ready-to-eat	22.3
Δ Reprocessed price-Primary price	-0.696
Rel. uncertainty of Δ	9.48%
p-value	2.30×10^{-6}

The results of this scenario allow for a better understanding of the substitution effect observed in scenario A2. With respect to their primary equivalents, reprocessed ready-to-eat products show lower prices, increased sustainability, and reduced quality. This analysis reveals how, thanks to reduced prices, reprocessed products can meet consumers' preferences despite being perceived as having lower quality.

This means reprocessed ready-to-eat products can maximize users' utility (Eq. 2), limiting the need to purchase other products. This characteristic of the system allows consumers to shift to reprocessed ready-to-eat products instead of increasing purchases. Therefore, it is possible to observe an emerging price elasticity of demand since the users' price sensitivity limits the total volume of purchases. The balance between sustainability preferences and price sensitivity explains how introducing reprocessed products in the system can increase the sustainability of purchased products without leading to increased overall consumption. These findings partially contradict the existing literature, as reported by Makov and Font Vivanco (2018) in the case of refurbished phones. The paper discusses how reconditioning used phones is not effective in reducing primary production since consumers perceive them as having a lower quality despite being cheaper than primary ones (Makov and Font Vivanco, 2018). This triggers an imperfect substitution and a rebound effect, as the demand for primary products is not reduced, and the overall demand increases due to increased purchases of refurbished products (Zink and Geyer, 2017). In contrast, the findings of this study suggest a more effective substitution. Ready-to-eat products, while cheaper than their primary equivalents, are more expensive than other product classes and meet consumers' needs. The combination of these two characteristics allows for limiting the demand for other food categories, thus avoiding the CER observed in other sectors. This is aligned with Siderius and Poldner (2021), who discuss how there is no direct association between a specific CE strategy and the risk of CER since it also depends upon market dynamics.

3.5 Scenario C

Scenario C evaluated the impact of varying the number of agents (users and companies) in the system, which is a typical strategy to assess the effect of entities' numerosity on the output variables under study Bertolotti and Roman (2024). It was observed that increasing the number of agents (both users and companies) reduced the uncertainty of key variables, consistently with existing literature. While sustainability continued to improve, the reduction in purchases became less pronounced as market diversity increased (see Table 6).

Table 6. Scenario C results.

Agents	Δ_P	Δ_S
Users = 50		
5 Companies	-0.213	0.223
10 Companies	-0.208	0.291
20 Companies	-0.205	0.318
Users = 100		
5 Companies	-0.220	0.263
10 Companies	-0.191	0.279
20 Companies	-0.180	0.302
Users = 200		
5 Companies	-0.224	0.268
10 Companies	-0.218	0.289
20 Companies	-0.176	0.290

The results show that, as the number of companies increases, consumers tend to substitute primary products with reprocessed ones at a lower degree. In this context, companies offer users a broader range of choices, including products that better meet individual preferences (Lancaster, 1966). Overall, this reduces the likelihood of users focusing on reprocessed products. This dynamic reflects an emergent balance between supply and consumer preferences, which leads to a less pronounced decline in purchases due to the increased supply and variety of products in the market. As supply increases, the substitution of primary products with reprocessed ones still occurs, even if at a more limited magnitude. Similar behavior can be observed in the free-from food market, where the increased availability of gluten-free, lactose-free, or plant-based and vegan products has significantly reshaped consumer choices. The free-from food market is no longer a niche segment, as it is preferred by a broader set of consumers who consider ingredients and sustainability in their purchases (Wunsch, 2014). Consumers with or without intolerances choose free-from food for several reasons, highlighting how more product options allow consumers to better align their purchases with individual values and preferences, ultimately influencing market dynamics (Savarese et al., 2021).

4. CONCLUSION

This work has explored CER dynamics in the food sector, which may arise following strategies to prevent or recover near-expiration food, reducing food waste. The creation of an ABM highlights the circumstances that may underpin CER in this context, allowing answering the research questions. Concerning RQ1, to capture and quantify CER we took into consideration the ratio of change in purchasing to the change in sustainability of products (i.e., the introduction of CE reprocessing practices), which evaluates the impact on consumption induced by the availability of reprocessed products and simulating the complexity of consumers' and companies' behaviors, as highlighted by (Koide et al., 2023). An agent-based model was created to this aim, taking into consideration the relationships between agents represented by companies and consumers. With respect to RQ2, concerning the reprocessing of food waste, the extent of reprocessing, the pricing of reprocessed products, and their ability to satisfy customers' needs are crucial elements that influence the overall sustainability of the system. In fact, the implementation of reprocessing strategies to a significant scale seems to affect the occurrence of a measurable CER. Our findings also show that with increased overall product availability, reprocessing keeps its positive effect in terms of sustainability, but the market stabilizes with a reduction in purchases that, while remaining present and certain, is less pronounced. This suggests that the impact of product availability and variety on the concentration of consumption also applies to the context under investigation. This work has several implications. From a theoretical standpoint, this study offers a deeper understanding of the systemic impacts of circular initiatives for near-expiration food. CER is underexplored in the food sector; therefore, the in-depth investigation presented in this study allows for isolating similarities and differences with other industrial sectors. Moreover, this work offers methodological contributions to the extant literature. The use of ABM underlines its potential as an ex-ante tool for estimating possible rebounds, as it can quantify CER and helps to isolate those circumstances under which CER can occur. This is also achieved with the formulation of Eq. 4, which can depict the presence of rebound effects. Since the literature does not provide a precise formula for CER, this represents a further theoretical contribution. Finally, this paper presents an agent-based meta-model, which could be further specified and employed to analyzed different industries and answer different research questions. From a practical perspective, the results provide guidance for food companies willing to engage in CE activities. The reprocessing of near-expiration food can reduce food waste and increase sustainability only if broadly executed, stressing the need for broad involvement in circular initiatives through scalable initiatives, since low levels of reprocessing could not be sufficient to offset potential rebound risks. Despite the discussed implications, some limitations of this work must be acknowledged. The model is a simplified abstraction and may not fully capture the complexities of real-world systems. While designed as a meta-model potentially applicable to various sectors, it assumes isomorphism between different sectors that may not hold in practice due to sector-specific dynamics. Additionally, the model presupposes that agents act to maximize utility, overlooking the possibility of irrational or alternative decision-making behaviors. Finally, as a proof of concept rather than a detailed representation of a real system, the model requires empirical validation to ensure the reliability and applicability of its findings across different contexts.

Future developments include the empirical validation of the model through the collection of data, its application to a case from a different industry to explore its broader applicability and refining its specifications to target not only an industry but also a specific market, such as the Italian food market. Efforts could also be directed towards enhancing the model to achieve more realistic consumer and company behavior. Additionally, the impact of specific combinations within the reprocessing matrix on the rebound effect could be investigated to better understand their influence on the overall system. Finally, as a simulation tool, this model could - with adjustments of data input and strategy-specific dynamics – be adapted to assess the impact also of other circular strategies before the actual implementation: this predictive analysis offers companies valuable insights to assess various circular initiatives and optimize them for sustainability outcomes.

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