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ARTICLE

From linear to circular pig farming: a systematic literature review

Da suinocultura linear para a circular: uma revisão sistemática de literatura

Gevair Campos[1], Vânia Ferreira Roque-Specht[2], Fabrício Oliveira Leitão[1]

[1]Programa de Pós-graduação em Agronegócios (PROPAGA/UnB), Universidade de Brasília (UnB), Brasília (DF), Brasil.
E-mails: javas1989@gmail.com; fabriciofol@hotmail.com
[2]Universidade de Brasília (UnB), Planaltina (DF), Brasil. E-mail: vaniars@unb.br

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Abstract: Pig farming, recognized as a pillar of global food production, faces the challenge of managing large volumes of waste, whose inadequate disposal generates significant environmental impacts. Therefore, this study sought to identify and analyze the circular economy (CE) strategies applied in the sector for waste management and valorization, using the 9R framework as an analytical basis to evaluate environmental policy maturity. The methodology consisted of a systematic literature review of articles published between 2015 and 2025. The initial categorization revealed that Pig Manure dominated the research, highlighting the literature's focus on the sector's main environmental liability. The integrated analysis mapped the predominant circular practices, indicating that the most explored solutions concentrated on the reactive end-of-waste cycle: Recovery (R9) of energy and Reuse (R3) of effluents. Proactive, higher-value strategies in the hierarchy, such as Refuse (R0), Rethink (R1), Repair (R4), and Refurbish (R5), proved to be completely absent or insufficiently explored. This concentration on end-of-cycle strategies reveals a profound "circularity gap" within the sector, which still operates predominantly under a "waste economy" model driven by rehabilitative circularity. The findings indicated the need to develop a theoretical proposition that promotes a shift from end-of-pipe impact mitigation to systemic preventive design, aiming at Refusing (R0), Rethinking (R1), and Redesigning (R7) the system to achieve full resource decoupling.

Keywords: circular economy, swine farming, 9R framework, waste valorization, sustainability.

Resumo: A suinocultura, reconhecida como um pilar da produção global de alimentos, enfrenta o desafio de gerenciar grandes volumes de resíduos, cujo descarte inadequado gera impactos ambientais significativos. Portanto, este estudo buscou identificar e analisar as estratégias de economia circular (EC) aplicadas no setor para a gestão e valorização de resíduos, utilizando a estrutura dos 9 Rs como base analítica para avaliar a maturidade da política ambiental. A metodologia consistiu em uma revisão sistemática da literatura de artigos publicados entre 2015 e 2025. A categorização inicial revelou que o Esterco Suíno dominou as pesquisas, destacando o foco da literatura no principal passivo ambiental do setor. A análise integrada mapeou as práticas circulares predominantes, indicando que as soluções mais exploradas se concentraram no ciclo reativo de fim de resíduo: Recuperação (R9) de energia e Reúso (R3) de efluentes. Estratégias proativas de maior valor na hierarquia, como Recusar (R0), Repensar (R1), Reparar (R4) e Remodelar (R5), demonstraram ser completamente ausentes ou insuficientemente exploradas. Essa concentração em estratégias de fim de ciclo revela um profundo "gap de circularidade" dentro do setor, que ainda opera predominantemente sob um modelo de "economia de resíduos" impulsionado por uma circularidade reabilitadora. Os achados indicaram a necessidade de desenvolver uma proposição teórica que promova uma mudança da mitigação de impactos de fim de ciclo para um design preventivo sistêmico, visando Recusar (R0), Repensar (R1) e Redesenhar (R7) o sistema para alcançar o desacoplamento total de recursos.

Palavras-chave: economia circular, suinocultura, framework 9R, gestão de resíduos, sustentabilidade.

1 Introduction

Swine farming is a vital global agricultural activity, underpinning food security and economies across numerous countries. This complex production chain spans from breeding and fattening to slaughter, processing, and product distribution for various forms of consumption. In the Brazilian context, the sector has evolved through complex boundary infrastructures connecting science, policy, and practice, especially within major production hubs (Vilas-Boas et al., 2022).

Traditional swine farming, especially in intensive systems like Confined Animal Feeding Operations (CAFOs), concentrates vast numbers of animals, leading to the generation of high volumes of organic waste and liquid effluents in restricted areas (Hollas et al., 2021; Cândido et al., 2022).

This conventional approach operates within the linear economy model, commonly termed "take-make-dispose" (Geissdoerfer et al., 2017). This model is inherently resource-intensive, demanding large quantities of natural resources such as water and feed, while treating manure and by-products as valueless waste (Hollas et al., 2022; Maj, 2022). Such a framework typically characterizes a reactive environmental policy, where management is limited to corrective strategies for end-of-cycle residues. Improper residue management creates severe environmental consequences, including the eutrophication of water bodies, soil pollution from nutrient excess, and greenhouse gas emissions, alongside the risk of pathogen spread (Hollas et al., 2022; Lin et al., 2022).

To address these critical challenges, swine farming is undergoing a necessary transition toward the Circular Economy (CE). This paradigm shift aims to establish a restorative and regenerative system that moves beyond the linear model (Kirchherr et al., 2017). The core objective of CE is to decouple economic growth from the consumption of finite resources by maintaining the value of materials, energy, and nutrients in continuous loops (Kirchherr et al., 2023; Cândido et al., 2022). Crucial to this transition is the 9 Rs framework (Refuse, Rethink, Reduce, Reuse, Repair, Refurbish, Remanufacture, Repurpose, Recycle, and Recover), which serves as a metric for environmental maturity. While a focus on the final Rs (Recycle, Recover) indicates a reactive stance, an emphasis on the initial, preventive Rs (Refuse, Rethink, Reduce) aligns the industry with a proactive environmental policy centered on resource efficiency and waste prevention. In this new framework, waste is reframed not as a liability but as a valuable resource, focusing on the valorization of generated biomass into new revenue streams.

Despite its promise, the large-scale shift to CE faces multifaceted challenges. These include a lack of conceptual and terminological consensus (Kirchherr et al., 2017), resistance to change, and technological limitations that impede cycle closure (Ghisellini et al., 2016). Furthermore, the adoption of circularity is heavily dictated by institutional and economic determinants; in regions like the European Union and China, central regulations and environmental supervision have significantly reshaped industrial layouts, though often with unintended impacts on production stability (Zheng et al., 2024; Ribašauskienė et al., 2023). Within intensive swine farming, these issues are compounded by the high cost of advanced technologies, operational complexity, scarcity of technical expertise (Lieder & Rashid, 2016), lack of engagement among stakeholders, and a deeply ingrained culture of disposal (Lieder & Rashid, 2016; Kirchherr et al., 2018).

Nonetheless, the integration of intensive swine farming with practices promoting waste reuse, nutrient recovery, and renewable energy generation robustly illustrates the application of CE principles in the agricultural sector. This integration reflects a shift toward a proactive model, where nutrient recovery (e.g., through duckweed ponds or struvite crystallization) and energy valorization transform potential pollutants into high-value inputs (Mohedano et al., 2012; Ha et al., 2024). Fundamentally, the CE seeks to foster sustainability and resilience by closing material and energy cycles, primarily to regenerate natural systems and reduce resource extraction and waste generation (Geissdoerfer et al., 2017). By proposing to maintain the economic and environmental value of products for as long as possible, CE offers a strategic response to resource scarcity and waste challenges (Lieder & Rashid, 2016).

Driving the CE requires key strategies, such as designing for product longevity, transitioning to service-based business models, and integrating clean technologies (Bocken et al., 2016).

Cooperation within industrial ecosystems and the development of closed-loop supply chains are also fundamental (Geissdoerfer et al., 2017; Ghisellini et al., 2016). In the Brazilian pig chain, decentralized and territorial intelligence-based business models are emerging as vital for overcoming logistical barriers and strengthening the regional bioeconomy (Pereira et al., 2023). Specifically in the swine sector, stable government policies that include financial incentives and favorable regulations are essential. The adoption of circular practices is further driven by strengthening the territorial economy through by-product valorization (Ferreira et al., 2023), increasing demand for sustainable food, and growing regulatory pressure related to renewable energy generation from swine manure.

Therefore, the primary objective of this study was to identify and analyze the CE strategies implemented in swine farming for waste management and valorization, using the 9 Rs framework as an analytical basis. Through a systematic review, the research aimed to identify gaps in the practical implementation of CE strategies, highlighting both those successfully applied for waste valorization and those that remain underexplored or limited in application. The study specifically evaluates the degree to which these strategies represent a shift from reactive, end-of-pipe solutions to proactive, preventive circular design. From a managerial standpoint, the research sought to provide industry actors with a clear overview of the most effective and prevalent CE strategies. By identifying existing gaps, the findings also inform policymakers about the necessity of targeted incentives and regulations to promote the adoption of a more comprehensive set of CE strategies, including vital prevention and design-focused measures. This study ultimately proposes that the transition of swine farming from a linear to a CE is predominantly characterized by the adoption of waste and effluent valorization strategies, indicating an initial focus on end-of-cycle optimization and impact mitigation, rather than a full systemic reconfiguration that integrates waste prevention and resource lifespan extension strategies.

2 Theoretical Foundation

Historically, industrial production has been fundamentally based on the linear economy model, widely known as "take-make-dispose" (Geissdoerfer et al., 2017). This system involves the extraction of natural resources, their transformation into products that are consumed, and their eventual discard as waste at the end of their useful life (Lieder & Rashid, 2016). This model is sustained by an institutional "lock-in" that prioritizes short-term economic gains over long-term ecological stability. This unidirectional flow is inherently unsustainable, operating under the unrealistic assumption of an infinite supply of resources and unlimited capacity for waste absorption. The increasing scarcity of resources and escalating waste generation have severely exposed the shortcomings of this model, compelling the search for more viable alternatives (Lieder & Rashid, 2016).

In response to the global sustainability crisis and the clear failures of the linear model, the CE emerges as a fundamental concept for a restorative and regenerative approach that actively moves beyond the linear cycle (Kirchherr et al., 2017). The transition to CE represents a paradigmatic shift from reactive, "end-of-pipe" environmental management toward proactive strategies rooted in eco-innovation and systemic design. The essence of CE lies in decoupling economic growth from the consumption of finite resources, thereby preserving the value of materials and products within the system for as long as possible (Kirchherr et al., 2017; Kirchherr et al., 2023). CE is considered a necessary transition to achieve balance between environmental and economic systems, promoting resource efficiency with a dedicated focus on industrial and urban waste management (Ghisellini et al., 2016; Korhonen et al., 2018).

While the concept of the CE is extensively discussed with varied definitions, all interpretations converge on the critical need for systemic change (Kirchherr et al., 2017; Geissdoerfer et al., 2017). Central to this systemic evolution is the 9R Framework, which serves as a hierarchical guide for circularity maturity. This hierarchy differentiates levels of environmental commitment based on the timing of intervention. Strategies of high circularity, defined as Proactive Policies (R0 - Refuse, R1 - Reduce, and R2 - Rethink), focus on the "smarter use and manufacturing" of products. These strategies define a proactive stance because they prioritize the prevention of waste generation at the design phase (Sossidou et al., 2025). In contrast, strategies of low circularity represent Reactive or Corrective Policies (R8 - Recycle and R9 - Recover), which focus on "useful application of materials" only after they have been discarded. While these latter strategies provide value recovery, they remain essentially corrective, as they do not challenge the underlying production volume or resource intensity (Ferreira et al., 2024). CE extends beyond simple recycling, representing a new sustainability paradigm that encompasses the entire life cycle of a product, from its initial design to its post-use phase (Geissdoerfer et al., 2017). The primary focus is to optimize production systems to create value loops, ensuring that what would be considered waste in a linear process becomes a valuable resource for another (Lieder et al., 2017). The most influential definition, proposed by the Ellen MacArthur Foundation (2013) and adopted in this work, describes CE as an intentionally restorative and regenerative industrial system (Geissdoerfer et al., 2017). This definition rests on three core principles: eliminating waste and pollution from the design stage, keeping products and materials in use for the maximum time possible, and regenerating natural systems.

The transition of swine farming to a circular model is gaining momentum through the adoption of practices and technologies that convert what was previously viewed as waste into high-value products. However, current efforts in the sector are predominantly restricted to the final stages of the 9R hierarchy, characterizing a reactive approach focused on mitigating the impacts of intensive production after waste has been generated (Cândido et al., 2022; Pexas & Kyriazakis, 2023). This focus on "end-of-pipe" solutions, such as anaerobic digestion and nutrient stripping, indicates that the sector is still transitioning toward a more circular state but has yet to embrace a fully proactive model centered on prevention (Folino et al., 2020). This shift not only creates new revenue streams but simultaneously reduces environmental impact. Implementing CE in this sector mitigates negative environmental externalities and unlocks significant economic opportunities via nutrient recovery and energy generation, securing a more sustainable future for the production chain (Cândido et al., 2022; Hollas et al., 2021; Zhou et al., 2024).

Despite these clear environmental and economic advantages, the transition to a circular model in swine farming faces substantial barriers that impede its large-scale adoption. Economic viability remains a major obstacle, largely attributed to the lack of stable markets for circular products and the absence of consistent government support and incentives (Kirchherr et al., 2018). The adoption of circularity is further dictated by diverse institutional determinants; while the European Union and China have implemented centralized regulatory frameworks and environmental supervision to force industrial reconfiguration (Zheng et al., 2024; Ribašauskienė et al., 2023), developing nations like Brazil still struggle with regulatory fragmentation and a lack of specific credit lines for the bioeconomy. Specifically, the scarcity of financial incentives and clear policies for developing a circular bioeconomy significantly hampers the implementation of necessary innovations (Feng et al., 2023).

Academic research on applying CE concepts in swine farming has overwhelmingly concentrated on specific circular technologies and practices. Crucially, a notable gap exists in explicitly linking the sector to a systemic analysis model like the 9R Framework. While many publications discuss circularity, focusing on activities such as anaerobic digestion for biogas or bioconversion of food waste into feed (Pinotti et al., 2023; Feng et al., 2023; Maj, 2022), they rarely utilize the 9R Framework as a holistic conceptual structure to analyze the sector's transition. Instead of providing a comprehensive description of barriers and opportunities across the entire hierarchy, research tends to address solutions in a fragmented manner, focusing on technical issues like pathogen removal (Lin et al., 2022) or the recovery of specific nutrients such as phosphorus and nitrogen (Cândido et al., 2022). This lack of integrated analysis suggests that although the sector is implementing certain circular practices, it remains anchored in a "corrective" mindset. The systematic understanding and application of a comprehensive model like the 9Rs have not yet become consolidated in the literature, particularly regarding strategies that require a fundamental "rethinking" of the production system (Kirchherr et al., 2017; Hasan et al., 2024).

Applying the 9R Framework offers the potential to move far beyond current manure recycling practices, promoting a deeper, integrated circularity that aligns production with principles of sustainability and economic resilience (Lieder & Rashid, 2016). By adopting a proactive stance, the industry can move up the hierarchy from simple "Reactive" recovery (R9) toward "Proactive" loops that narrow and slow the resource cycle. The true transition begins with Rethinking (R2) the business model and the use of smart technologies (Mahfuz et al., 2022) to minimize dependence on external inputs like grains and synthetic fertilizers. For instance, the industry could prioritize the bioconversion of food waste and other by-products into animal feed (Pinotti et al., 2023). This approach not only creates a more efficient system but also makes production less vulnerable to commodity market fluctuations. Concurrently, strategies focused on Reduce (R1) through precision feeding and the Refuse (R0) of inefficient processes can minimize resource consumption and the carbon footprint from the source (Hasan et al., 2024; Bocken et al., 2016). Concurrently, strategies focused on Repair (R4) farm infrastructure and equipment can extend asset lifespans, consequently minimizing the need for new purchases (Tukker, 2015). The concept of Remanufacturing (R6), commonly used in industrial sectors, can be adapted by developing service-based business models where specialized companies recover and recondition worn equipment components. This adds economic value while contributing to circularity by retaining high-quality materials in use longer (Lieder et al., 2017). Finally, Regeneration emerges as one of the most transformative principles, enabling the sector to use manure not just as recycled material but as a means to regenerate agricultural ecosystems. The application of nutrient-rich digestate from anaerobic digestion can enrich the soil, boosting organic matter and improving long-term soil health and biodiversity (Silva et al., 2025; Hollas et al., 2022). The strategic use of biochar as an additive can further enhance the benefits of the digestate, yielding a premium-quality fertilizer (Silva et al., 2025).

3 Methodology

This section details the methodology employed for the systematic review, focusing on circular strategies applied in swine farming, with a strong emphasis on waste management and valorization. The methodological design was rigorously structured following the guidelines of the Preferred Reporting Items for Systematic Review and Meta-Analysis Protocols (PRISMA-P 2015) (Moher et al., 2015). This protocol was selected to provide a transparent and replicable audit trail, essential for identifying the institutional and technological determinants that govern the transition from linear to circular systems. The selection of the PRISMA protocol is justified by its capacity to ensure transparency, integrity, accuracy, and reproducibility of the review process. This standardized approach is widely recognized in systematic reviews on the CE, as demonstrated by other researchers who utilized PRISMA to guarantee a structured and comprehensive approach to the search, assessment, and data extraction from the literature (Abdelmeguid et al., 2022; AlJaber et al., 2023).

3.1 Search strategy and study selection

The bibliographic search was conducted in two extensive international databases: Web of Science and Scopus. These platforms were chosen due to their recognized credibility as primary sources of peer-reviewed literature, covering fields essential to the research scope, such as agricultural sciences and environmental engineering (Rótolo et al., 2022; Lieder & Rashid, 2016; Ghisellini et al., 2016; Geissdoerfer et al., 2017). The use of these databases ensures a high "bibliometric density," capturing the intersection between technological innovation and environmental policy within the global agri-food system. Their suitability for systematic reviews in CE was further supported by their use in related works exploring CE barriers (Abdelmeguid et al., 2022; AlJaber et al., 2023). Their multidisciplinary nature and wide journal indexing ensured extensive coverage of publications on CE in swine farming.

The search strategy was designed to maximize the retrieval of relevant articles. Search terms were combined and applied to the Title, Abstract, Keyword Plus, and Author Keywords fields to ensure relevance. The search utilized the following query: *(("Circular economy" OR "circularity") AND ("pig" OR "pigs" OR "swine" OR "pork"))*

This combination of terms was developed to encompass studies on CE and its connection with the swine supply chain. The publication period was restricted between 2015 and 2025, allowing the analysis of recent trends and the state-of-the-art in the field (Ghisellini et al., 2016; Lieder & Rashid, 2016). This timeframe is particularly relevant as it coincides with the post-Paris Agreement era and the intensification of "green growth" policies in major swine-producing regions. Only Articles were considered, excluding other document types to focus on high-quality research and reviews. The search, conducted on June 27, 2025, resulted in the identification of 253 articles in Web of Science and 254 articles in Scopus.

3.2 Records management and screening

All retrieved records were imported into Microsoft Excel software for organization, removal of duplicates, and efficient flow management. Screening followed the PRISMA flow diagram (Figure 1), adapted from Moher et al. (2015), to ensure traceability and reproducibility of the selection process. This systematic filtration process was designed to eliminate studies that focused solely on isolated technical parameters without offering insights into the systemic circularity of the production chain. This approach is widely used in systematic reviews on the CE, reinforcing methodological rigor (Boloy et al., 2021; Di Vaio et al., 2023).

After deduplication, 303 records were subjected to title and abstract analysis, resulting in the exclusion of 166 irrelevant records. In the eligibility phase, 137 full texts were sought, and 131 obtained. After detailed evaluation, 61 articles were excluded for not meeting the criteria, consolidating a final sample of 70 studies.

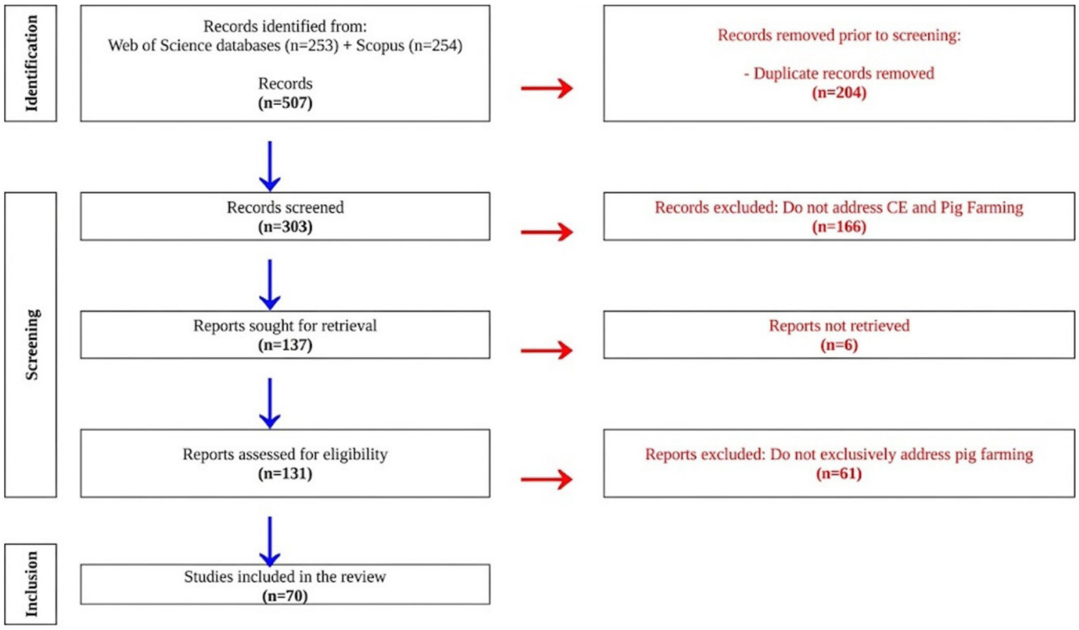

Figure 1. PRISMA flow diagram of study selection
Source: Adapted from PRISMA. PRISMA Statement (2026)

3.3 Eligibility criteria

To ensure the validity and relevance of this systematic review, objective inclusion and exclusion criteria were established, given the multifaceted nature of CE (Kirchherr et al., 2017). Rigor in selection was fundamental to guarantee the quality of analyzed articles.

Inclusion criteria focused on thematic specificity and credibility: Articles addressing CE practices directly applied to swine farming; Peer-reviewed publications indexed in the Web of Science and Scopus databases. Specifically, studies had to provide clear evidence of resource loop closure or the valorization of externalities.

Exclusion criteria aimed to refine the sample: Studies lacking clear focus on swine farming and CE practices; Studies addressing mixed waste from other species without relevance to swine CE; Literature review or conceptual articles without empirical CE application in swine farming (Lieder & Rashid, 2016; Ghisellini et al., 2016); Lack of access to the full text. Additionally, studies that treated waste solely as a disposal problem without considering its potential as an input for other processes were excluded.

Systematic application of these criteria resulted in the final sample of 70 articles, providing a solid basis for analysis.

3.4 Final sample and research question

The final sample for this systematic review comprises 70 articles that fully meet the inclusion criteria. This robust sample will be used to answer the following research question (RQ1), which guides the synthesis of results:

RQ1: To what extent are the strategies of the 9R framework applied in swine farming,ranging from reactive (end-of-pipe) to proactive (preventive) policies, for waste management and valorization?

3.5 Data analysis

Data from the 70 articles were subjected to qualitative analysis to answer the proposed research question. The analytical lens was grounded in the distinction between "Slowing," "Closing," and "Narrowing" resource loops (Bocken et al., 2016), mapped against the 9R hierarchy. The analysis categorized studies based on the following thematic axes: types of swine farming waste, geographical location of research, and strategies according to the 9R framework. This categorization enabled mapping the connections between wastes (such as manure, wastewater, and digestate) and the circular strategies applied. Finally, theoretical propositions and managerial implications were developed based on the findings.

Crucially, the 9R framework was used to assess the maturity of the environmental policies identified in the literature:

- Reactive/Corrective Strategies: Focused on R8 (Recycle) and R9 (Recover), typically associated with traditional waste management.
- Transitional Strategies: Focused on R3 to R7.
- Proactive/Preventive Strategies: Focused on R0 (Refuse), R1 (Rethink), and R2 (Reduce), representing advanced circular design.

The integrated analysis allowed for the identification of predominant circular practices for each waste type, revealing implementation patterns, literature gaps, and emerging trends. This enabled a critical evaluation of whether the sector is merely optimizing its "end-of-pipe" residues or undergoing a true systemic reconfiguration. Synergies between waste types and circular solutions, as well as barriers to adopting these practices, were highlighted. This approach contributed to a critical understanding of CE applied to the swine farming sector, assessing the suitability of proposed solutions according to waste characteristics and structural conditions, aligning with circularity principles in industrial production (Lieder & Rashid, 2016).

The study's analytical framework, focused on strategies for circular swine farming, was structured based on the 9R framework. Comprising nine main categories, it enabled an in-depth analysis of CE approaches in the sector. Although inspired by previous studies (Esposito et al., 2020; Bisogno et al., 2018; Manes-Rossi et al., 2020), the framework was adapted to reflect swine farming specificities, ensuring that biological cycles (bio-based loops) were properly distinguished from technical cycles. This adaptation was fundamental to identifying complexities in circular transition in this sector, as evidenced in reviews on CE implementation in other industries (Lieder & Rashid, 2016; Ghisellini et al., 2016).

The data analysis addressed the following categories (Table 1):

Table 1. Conceptual framework with classification and codes for study analysis

Category	Subcategory	Description	Citations
A: Type of Waste	A1: Swine Manure (Swine/Pig manure/ slurry/manure effluent)	Includes feces, slurry, and manure effluents.	(Yost et al., 2022; Silva et al., 2025; Cardoso et al., 2015)
	A2: Swine Wastewater	Comprises wasted water, cleaning water, and undigested food residues.	(Zhou et al., 2024; Wu et al., 2023)
	A3: Anaerobic Digestion By-products (Digestate)	Defined as the liquid effluent resulting from the Anaerobic Digestion (AD) process of swine manure.	(Silva et al., 2025)
	A4: Other Organic Waste	Encompasses specific organic wastes such as animal carcasses and placentas.	(Yost et al., 2022; Pinto et al., 2022)

Source: Research data.

Table 1. Continued...

Category	Subcategory	Description	Citations
B: Research Location	B1: Europe	Geographic location of studies in Europe.	(Esposito et al., 2020; Bisogno et al., 2018; Manes-Rossi et al., 2020)
	B2: America	Geographic location of studies in America.	
	B3: Africa	Geographic location of studies in Africa.	
	B4: Asia	Geographic location of studies in Asia.	
	B5: Oceania	Geographic location of studies in Oceania.	
	B6: Mixed	Studies covering multiple regions, not specified as worldwide.	
	B7: Worldwide	Studies with global scope.	
	B8: None	Studies without specific geographic focus.	
R: CE Strategies	R0: Refuse	Avoid the use of raw materials and consumption of unnecessary products, preventing the problem at the source.	(Potting et al., 2017; Van Buren et al., 2016; Kirchherr et al., 2017)
	R1: Rethink	Rethink business models or product design, for example, through sharing.	
	R2: Reduce	Reduce the use of raw materials, resource consumption, and increase production efficiency.	
	R3: Reuse	Reuse the product or its parts, such as buying and selling second-hand products or sharing.	
	R4: Repair	Perform maintenance and repairs to keep the product functioning.	
	R5: Refurbish/Restore	Remodel or restore a product to improve its quality and extend its useful life.	
	R6: Remanufacture	Create new products from (parts of) old products while maintaining the original function.	
	R7: Redesign/Readapt	Reuse the product, wholly or partially, for a different purpose than the original.	
	R8: Recycle	Process and reuse materials, usually with quality loss (downcycling).	
	R9: Recover	Incinerate residual flows to recover energy, the last option in the hierarchy.	

Source: Research data.

These categories served as the basis for categorizing and analyzing the studies, enabling the identification of patterns, gaps, and emerging trends in the literature on CE in swine farming.

4 Results and Discussion

This section provides a detailed analysis of the strategies associated with the 9Rs framework as specifically applied to swine farming, examining how each contributes to sustainability and efficiency in the sector.

4.1 Characterization of studies by waste type

The analysis of the studies, detailed by waste type in Table 2, revealed a clear concentration of research in specific categories. There was a predominance of Pig Manure (A1) as the most frequent individual focus, totaling 31 occurrences. This high frequency underscores the centrality of this waste in CE investigations applied to swine farming, reflecting its substantial volume and environmental impact. This concentration suggests that circularity in the sector is still primarily driven by the need to manage the most significant environmental liability (manure), often remaining at the lower levels of the 9R hierarchy, such as Recycle (R8) and Recover (R9). Following this, Other Organic Waste (A4) and Pig Wastewater (A2) were the next most studied individual waste types, with 8 and 7 occurrences, respectively. In contrast, Anaerobic Digestion By-products (A3) were the least studied individual waste type, with only 3 occurrences, matching the frequency of the "A5: None" category. The limited focus on Anaerobic Digestion By-products (A3) highlights a critical "circularity gap," as the full potential of the nutrient loop remains underexploited if the digestate is treated solely as a final residue rather than a high-value input for soil regeneration.

Table 2. Studies by waste type

Category Waste Type (A)	Frequency
A1: Swine Manure	31
A1: Swine Manure, A4: Other Organic Waste	10
A4: Other Organic Waste	8
A2: Swine Wastewater	7
A3: Anaerobic Digestion By-products	3
A5: None	3
A1: Swine Manure, A2: Swine Wastewater	2
A1: Swine Manure, A2: Swine Wastewater, A3: Anaerobic Digestion By-products	2
A1: Swine Manure, A3: Anaerobic Digestion By-products	1
A2: Swine Wastewater, A3: Anaerobic Digestion By-products	1
A1: Swine Manure, A2: Swine Wastewater, A4: Other Organic Waste	1
A1: Swine Manure, A3: Anaerobic Digestion By-products, A4: Other Organic Waste	1

Source: Research data.

Regarding waste combinations, the association between Pig Manure (A1) and Other Organic Waste (A4) was the most significant pairing, recording 10 occurrences, which represents the second-highest frequency in the table and strongly suggests a common practice of co-processing these materials in research, as demonstrated by examples such as Azevedo et al. (2021) analyzing the anaerobic co-digestion of pig slurry (A1) with bio-residue liquor from pineapple peel (A4); Macedo et al. (2023) focusing on the anaerobic co-digestion of piglet slurry (A1) with nanofiltration concentrates of mango peel (A4); Eduria et al. (2024) exploring optimized biogas production from pig manure (A1) and acid-hydrolyzed corn cob (A4); and Cong et al. (2024) mentioning the anaerobic co-digestion of the solid separated fraction of pig slurry (A1) with dried grass silage (A4). This trend toward co-digestion strategies exemplifies the transition from simple waste treatment to the creation of synergistic "closing loops" that optimize energy and nutrient recovery.

Other combinations involving multiple waste types exhibited significantly lower frequencies, indicating a preference for single-waste or dominant combination approaches. For example, the combination of Pig Manure (A1) with Pig Wastewater (A2) had only two occurrences (Jurkėnaitė, 2023; Molina-Moreno et al., 2017). Similarly, the triad of Pig Manure (A1), Pig Wastewater (A2), and Anaerobic Digestion By-products (A3) was addressed in only two research pieces (Cândido et al., 2022; Lee & Tsai, 2020). Remaining, more integrated combinations were identified with a minimum frequency of one occurrence. This distribution reinforces the conclusion that, despite diverse possible integrated approaches, most of the research focus concentrated on a single waste type (A1) or the dominant combination for co-digestion (A1, A4), revealing a need for more systemic studies that encompass the entire effluent management chain.

The None (A5) category, recorded in 3 occurrences, suggests situations where studies did not directly address the identification or application of specific wastes (A1, A2, A3, A4). This category included research focusing on broader aspects of swine production systems, such as barriers and drivers for outdoor access (Brajon et al., 2024), without primary waste categorization. In contrast, other studies focused directly on waste valorization through feed substitution, such as replacing barley with dehydrated orange pulp in pig diets (Ferrer et al., 2022) or incorporating olive oil by-products in feed (Paié-Ribeiro et al., 2025), highlighting diverse approaches in swine farming waste management. These approaches align with higher-level circular strategies such as Rethink (R1) and Reduce (R2) by incorporating industrial by-products back into the biological cycle of animal nutrition.

4.2 Research location

Europe (B1) was the leader in overall research distribution, with 32 studies recorded, suggesting the region plays a key role in the shift of the swine farming paradigm toward the CE. This leadership is intrinsically linked to robust institutional determinants, such as the EU Green Deal and the CE Action Plan, which promote a transitional bioeconomy through strict nitrogen and phosphorus regulations (Pexas & Kyriazakis, 2023). This inference is predominantly environmental, as concerns related to Pig Manure (A1), the main waste by volume and thematic focus, were present in 26 of these European studies, indicating a concentrated effort on managing and valorizing this by-product. A more detailed country-level analysis reveals that Spain stands out with the highest number of studies (13), aligning with the high concentration of research in Europe and its status as a major production hub under intense regulatory pressure to mitigate environmental hotspots.

Asia (B4) ranks second, with 20 studies, showing considerable activity. A significant portion of this output (10 studies) is concentrated in China, reflecting a top-down institutional shift driven by the "Zero-Waste City" initiative and the 14th Five-Year Plan for Rural Bioeconomy. These policies have catalyzed research into precision large-scale operations and the integration of smart technologies to resolve the conflict between production expansion and environmental supervision (Zheng et al., 2024; Hasan et al., 2024). The identified Chinese studies primarily focus on bioconversion and the systematic reconfiguration of manure management to support national food security and ecological civilization goals.

The Americas (B2) present a moderate number of 15 studies, with Brazil holding second place globally (12 studies). This prominence underscores Brazil's relevance in the global market and its unique trajectory of circularity, evolved through complex boundary infrastructures that connect science and policy (Vilas-Boas et al., 2022). Brazilian research emphasizes territorial intelligence and the decentralized valorization of by-products, specifically biogas and biomethane, as a strategic response to logistical barriers and the need for regional resilience (Pereira et al., 2023). Africa (B3) registers a very low count, with only 1 study, possibly indicating less academic focus or fewer published studies on this continent concerning CE in swine farming. The None (B8) category, with 2 studies, refers to cases where the research country was unspecified or did not fall clearly into a continental category.

The distribution reinforces the conclusion that circularity maturity is geographically heterogeneous and heavily dependent on regional regulatory frameworks and technological infrastructure.

4.3 Circular economy strategies in swine farming

This section presents a detailed analysis of the CE strategies identified in the studies, aligned with the 9R Framework and categorized by their frequency of occurrence. From the perspective of environmental policy maturity, these results allow for the classification of the sector into three stages: reactive (R8-R9), transition (R3-R7), and proactive (R0-R2).

Figure 2 details the frequency of occurrence of various CE strategies identified in the studies, aligned with increasing circularity and compared to the linear economy. The results show that the strategy of Recover (R9), associated with the incineration of waste with energy recovery and often positioned closest to the linear economy as an "end-of-pipe" solution, exhibits the highest frequency, with 65 occurrences. This overwhelming predominance of R9 indicates that the industry is still anchored in a reactive environmental policy, focused on corrective strategies to treat residues after their generation rather than preventing them (Ferreira et al., 2024). Following this, the strategy of Reuse (R3), related to extending the lifespan of products and parts without significant processing, demonstrates the second highest frequency, with 56 records. R3 represents a critical transition stage, where the management of existing material moves beyond simple disposal toward circular loops, though it remains largely dependent on the initial waste output. Reduce (R2), which involves smarter use and more efficient resource consumption during production, recorded 29 occurrences. Recycle (R8), also associated with the useful application of materials through processing into new raw materials, reached 15 occurrences. The fact that R8, another corrective/reactive strategy, remains prominent further reinforces the "waste economy" characterization of current research.

Strategies Rethink (R1) and Redesign/Readapt (R7) registered only 7 and 6 records, respectively. These strategies are pillars of a proactive environmental policy; their low representation suggests that systemic eco-design and high-order circularity are not yet prioritized in the sector (Sossidou et al., 2025). Crucially, the strategies of Refuse (R0), Repair (R4), Refurbish (R5), and Remanufacture (R6) showed zero occurrences. This complete absence of high-order circularity strategies demonstrates a profound "circularity gap" in swine farming, revealing a lack of preventive research aimed at eliminating waste before its creation. This multiplicity of approaches reflects the complexity of the CE definition, which is frequently seen as a combination of reduction, reuse, and recycling activities (Kirchherr et al., 2017).

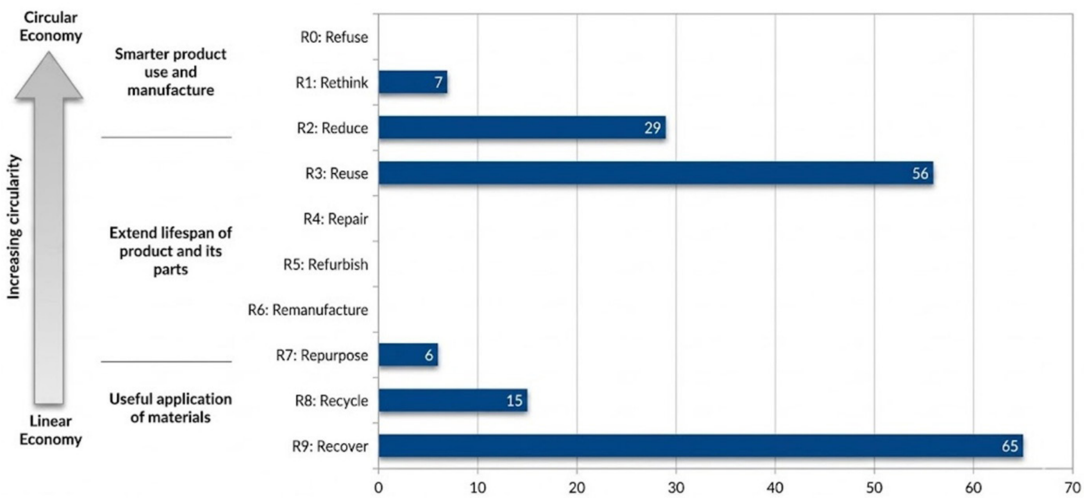

Figure 2. 9R Framework in Pig Farming
Source: Research data

The combination of strategies R3 and R9 (Reuse, Recover) was the most common, with 27 occurrences, indicating a strong focus on cascading material reuse and resource recovery in swine farming. This linkage characterizes a traditional "end-of-pipe" focus, where circularity is synonymous with effluent valorization. The second most frequent combination was R2, R3, R9 (Reduce, Reuse, Recover), with 12 occurrences, suggesting that efficiency gains combined with reuse and recovery is a maturing paradigm that seeks to balance productivity with waste minimization. However, this balance still leans heavily toward managing generated residues rather than systemic prevention.

Combinations R3, R8, R9 (Reuse, Recycle, Recover) and R2, R9 (Reduce, Recover) appeared 4 times each. The presence of R8 (Recycle) in these combinations highlights the importance of transforming biowaste into new resources, such as composting and nutrient recovery, thereby complementing reuse and recovery actions. While useful, these combinations remain within the corrective stage of the maturity model (López-Pacheco et al., 2021). The individual strategy R3 (Reuse) and the broader combination R2, R3, R8, R9 (Reduce, Reuse, Recycle, Recover) were recorded 3 times each, showing that although less frequent individually, reuse remains a key pillar, and integrating multiple circularity strategies occurs in more sophisticated system-level approaches. Other strategies and combinations appear less frequently, with one or two occurrences, indicating less common or more specific approaches in the analyzed studies.

These data confirm that swine farming research operates under a "waste economy" model rather than a systemic CE. The focus is almost exclusively on the output stage (downstream), indicating a reactive stance. Swine farming research tends to address Rethinking (R1) and Redesigning (R7) as secondary considerations integrated with more operational waste management strategies like reuse, recycling, and recovery.

The Rethink strategy in swine farming involves redefining processes and systems for circularity and sustainability. In a proactive model, rethinking must address the root causes of environmental pressure (Pexas & Kyriazakis, 2023). As proposed by Potting et al. (2017), product chain innovation is fundamental for the CE transition. Studies propose new models to optimize the value chain and improve waste management. For instance, Jeng et al. (2024) suggest a closed-loop model for pig manure reuse, seeking economic and environmental benefits, while Møller et al. (2024) emphasize the use of circularity indicators to transition systems toward agricultural sustainability. Other research addresses Rethink by considering: understanding producers' needs to drive innovations and improve animal welfare (Brajon et al., 2024); investigating circularity in organic farms to boost resilience (Pfeifer et al., 2022); proposing alternative schemes in the pork value chain (Noya et al., 2017); and measuring CE in production (Secco et al., 2020). Tong et al. (2023) even suggest systemic changes in dietary patterns, such as reducing pork consumption, to promote a circular bioeconomy.

The Redesign/Readapt strategy involves transforming swine farming waste into new products or inputs, extending beyond the farm to encompass the entire value chain. Transitioning to a proactive model requires redesigning the biological and technical cycles to ensure materials remain in high-value loops (Folino et al., 2020). Zhang et al. (2022) demonstrated the conversion of waste into functionalized biochar and medium-chain carboxylic acids, exemplifying material valorization through chemical readaptation. Noya et al. (2017) and Pereira et al. (2023) discuss creating new business models and value chains, which implies a structural redesign of the swine farming system. Dandamudi et al. (2021) proposed functionalized biochar development from microalgae and pig manure, with potential construction applications. Furthermore, Ferrer et al. (2022) redesigned pig diets by replacing barley with dehydrated orange pulp, readapting the use of agricultural by-products in animal feed. These efforts, while infrequent, represent the emerging proactive frontier of the sector.

The Reduce strategy in swine farming focuses on mitigating environmental impacts and optimizing resource use. The adoption of smart technology and precision farming is the primary driver for moving this strategy into the proactive/preventive domain (Mahfuz et al., 2022). Studies demonstrate effective practices for emission reduction and efficient resource consumption. Recent research shows significant advances in nutrient recovery, such as the report by Pinatha et al. (2025) that over 85% of phosphorus in pig wastewater can be recovered as struvite. Proskynitopoulou et al. (2024) reduced suspended solids and antibiotics in pig manure digestate, improving water quality. Pu et al. (2025) demonstrated reduced synthetic fertilizer needs by applying manure liquid to soil. Regarding emissions, Soto-Herranz et al. (2022) focused on reducing ammonia from pig slurry. Tong et al. (2023) proposed technological changes in feed production to reduce the environmental footprint. Xue et al. (2019) and Zhu et al. (2023) showed how CE and biogas use can reduce carbon emissions and improve soil quality. Water use optimization is explored by Vásquez et al. (2024). Veuthey et al. (2022) achieved cost reduction and contamination prevention by using effluents for microalgae cultivation. When coupled with precision large-scale operations, “Reduce” transitions from mere eco-efficiency to a proactive preventative strategy (Hasan et al., 2024).

4.4 Theoretical proposition of the study

The research reveals a significant focus on circular strategies closest to the “end-of-life” stage of materials, transforming waste into value, often at the expense of preventive approaches or those extending resource lifespan. The most prevalent strategies are Reuse (R3) and Recover (R9), which combined represent the majority of occurrences in the analyzed literature. This combination illustrates the current starting point for circularity in swine farming, with practical examples including treated water reuse for cleaning and irrigation (Lee & Tsai, 2020; Giang et al., 2021; Bortoli et al., 2022; Cândido et al., 2022) and bioenergy production from waste (Lee & Tsai, 2020; Secco et al., 2020; Azevedo et al., 2021; Hollas et al., 2022; Pereira et al., 2023). This pattern confirms that the sector is defined by a “rehabilitative circularity,” where the primary objective is to manage the liabilities of intensive production through reactive, end-of-pipe solutions (Ferreira et al., 2024). This aligns with the traditional definition of CE as a combination of reduce, reuse, and recycle (Kirchherr et al., 2017), but highlights a conceptual stagnation that limits the sector to corrective actions.

The Reduce (R2) strategy is also a key pillar, appearing frequently in combinations (R2, R3, R9) and reflecting the pursuit of efficiency and waste minimization at the source. Studies demonstrate phosphorus reduction in wastewater and decreased synthetic fertilizer needs (Pinatha et al., 2025; Pu et al., 2025), along with the mitigation of environmental impact and greenhouse gas emissions (El Bied et al., 2024; Ferrer et al., 2022). While R2 indicates an evolution toward eco-efficiency, it often remains tied to incremental improvements in existing linear processes rather than a fundamental decoupling of resource use from production growth. The Recycle (R8) strategy is less common, but its presence in combinations like R3, R8, R9 underscores the importance of transforming biowaste into new resources (Secco et al., 2020; Zalewska et al., 2023; Huyen et al., 2024; Su et al., 2024).

The integrated synthesis of this study enabled the construction of a conceptual framework leading to the following theoretical proposition: The transition from linear to circular swine farming is currently fragmented and hierarchically stagnant, characterized by a “circularity gap” where the adoption of reactive waste valorization (R9/R8) masks the absence of proactive preventive strategies (R0/R1). This indicates an operational model of “waste economy” that mitigates impacts at the expense of a comprehensive systemic reconfiguration (Rethink and Redesign) necessary for a true Circular Bioeconomy.

The predominance of R3 and R9 strategies and their frequent combination with R2 and R8 emphasize a focus on valorizing waste and effluents. Conversely, Rethink (R1) and Redesign/Readapt (R7), which require systemic change in the value chain (Potting et al., 2017; Van Buren et al., 2016), are less common. This suggests research still has a long way to go to address CE more fundamentally. The absence of R0, R4, R5, and R6 reveals that the sector's technical and biological cycles are not yet proactive, maintaining a dependency on high-input models that are only "circularized" at the final output stage (Pexas & Kyriazakis, 2023). The transition to a truly systemic CE model still has a long path ahead. The gap in these areas signifies a critical opportunity for future research and policies to move beyond mere waste management toward prevention and the design of more complete and effective circular systems.

4.5 Managerial implications

Based on the research findings, the swine production chain currently exhibits a dominant focus on end-of-life strategies. The observed high frequency of Reuse (R3) and Recover (R9) indicates that managerial efforts are heavily concentrated on waste and effluent valorization. For decision-makers, this focus suggests that circularity is currently viewed as a corrective environmental policy, a risk-management tool for environmental compliance rather than a proactive driver of business innovation (Hasan et al., 2024). While companies have achieved maturity in waste management, there is a critical need to shift toward a proactive environmental policy that includes prevention and optimization actions from the earliest stages of production.

The Reduce (R2) and Recycle (R8) strategies were found to be less frequent compared to R3 and R9. This finding points to a significant operational opportunity for managers to more actively integrate waste and emission minimization efforts. Adopting a proactive stance through precision feeding and real-time monitoring of resource flows could lead to fundamental resource decoupling (Mahfuz et al., 2022). The presence of R8 suggests a clear potential to transform biowaste into higher-value products such as specialized fertilizers and biochar, thereby opening new revenue possibilities beyond traditional by-products.

The strategies of Rethink (R1) and Redesign/Readapt (R7) were the least frequent, clearly evidencing a managerial and systemic gap. This requires a shift from "production management" to "proactive value chain coordination," where managers seek strategic partnerships to co-create value through preventive design. Instead of merely managing generated waste, it is essential to innovate processes so that circularity becomes an intrinsic feature of the activity, embedding material loops and resource efficiency from conception.

In summary, this research provides a clear managerial roadmap. The sector must strategically expand its focus from the reactive downstream stages (R3 and R9) to the proactive upstream production stages (Rethink and Redesign/Readapt). This transition from a "waste management" mindset to a "systemic preventive design" is vital for achieving resilience, better alignment with environmental regulations, and a sustainable competitive advantage in a circular bioeconomy.

5 Conclusions

The systematic assessment of circular strategies in the swine sector reveals a structural dependency on end-of-pipe interventions, characterizing a reactive environmental policy that prioritizes the mitigation of externalities over the prevention of their genesis. This prevailing "waste economy" model currently defines the sector's maturity, where circularity is applied as a rehabilitative measure rather than a regenerative design. A genuine transition toward a proactive circular model requires a shift from managing "outputs" to optimizing "inputs," ensuring that materials and energy remain in high-value loops through systemic design and structural innovation that transcends the current conceptual plateau of mere waste treatment.

The strategies most widely implemented are Reuse (R3) and Recover (R9), often occurring in combination to address the sector's main effluents. While this operational maturity in resource recovery, particularly through anaerobic digestion and nutrient stripping, confirms that the industry has consolidated the technical capacity to valorize residues, it also underscores a reactive stance where environmental management is limited to the end-of-waste cycle. Furthermore, the Reduce (R2) strategy is primarily applied as an incremental optimization of existing linear processes, such as the selective reduction of ammonia and suspended solids, rather than as a radical narrowing of resource loops. Recycling (R8) functions as a vital secondary loop that reintroduces biological materials into territorial circuits, yet its current application reinforces a corrective paradigm that fails to achieve a full decoupling of resource use from production growth.

Despite these efforts, a profound "circularity gap" persists regarding proactive, high-order strategies that define a preventive environmental policy. The total absence of Refuse (R0), Repair (R4), Refurbish (R5), and Remanufacture (R6) strategies reflects a systemic neglect of resource lifespan extension and the maintenance of technical assets within the production system. While Rethink (R1) and Redesign (R7) are emerging in the literature, their marginal presence indicates that the transition remains technically driven rather than strategically led. This lack of high-order circularity demonstrates that the sector has yet to move from "downstream" valorization to "upstream" prevention, leaving the core linear drivers of the industry largely unchallenged.

To bridge this gap and catalyze the evolution from a "waste-centric" model to a holistic circular bioeconomy, future research must prioritize three analytical fronts. Investigations should advance toward "Refusal" (R0) and "Rethink" (R1) through precision nutrition and smart technologies that eliminate nutrient surpluses at the point of origin, thereby transforming the geochemical balance of the system. Scholars must explore the economic feasibility of extending the durability of farm infrastructure (R4 and R5) through service-based business models, addressing the lack of data on how asset longevity influences capital efficiency and the sector's total carbon footprint. Finally, the academic agenda should move beyond isolated technical fixes to propose redesigned production systems (R7) that utilize territorial intelligence and multi-stakeholder partnerships to create industrial ecosystems where waste is not an inevitable outcome, but a designed-out inefficiency. In conclusion, while the swine sector has mastered the art of valorizing its residues, its future resilience depends on its capacity to rethink its fundamental architecture, shifting from a reactive model that cleans up after production to a proactive one that produces within the limits of biological and technical cycles.

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GC: Writing – review & editing, Writing – original draft, Visualization, Validation, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. VFRS: Validation, Supervision, Methodology, Investigation, Formal analysis, Conceptualization. FOL: Validation, Methodology, Investigation, Formal analysis, Conceptualization.

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Corresponding author:

Gevair Campos. javas1989@gmail.com

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