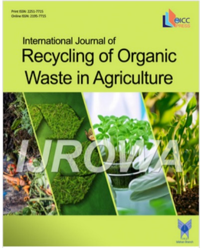

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Systematic literature review on the utilization of tuber crop skins in the context of circular agriculture

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Abstract:
Purpose: This Systematic Literature Review (SLR) investigates the utilization of tuber crop skins, specifically from yam, potato, taro, and cassava as an underexplored resource in circular agriculture. The study aims to assess their multifaceted applications across sectors such as animal feed, bioenergy, material science, wastewater treatment, and food innovation, addressing the overarching research question of how tuber crop skins can contribute to a more sustainable agricultural model.
Method: A rigorous review protocol was applied to analyze 26 articles sourced from ScienceDirect and Web of Science. The selection criteria focused on works that explore the application of tuber crop skins in various do-mains, ensuring a comprehensive coverage of the subject matter.
Results: The analysis reveals that tuber crop skins offer significant benefits, including serving as nutrient-rich livestock feed, potential bioenergy feedstocks, and a basis for bio-based plastics and biocomposites due to their high cellulose, hemicellulose, and lignin content. Their capacity for absorbing pollutants also highlights their utility in wastewater treatment. Additionally, their application in food fortification and the creation of function-al foods showcases their versatility.
Conclusion: Despite the promising applications of tuber crop skins, there is a notable lack of comprehensive studies examining their long-term sustainability, scalability, and socio-economic impacts. The research identifies a crucial need for interdisciplinary studies to address these gaps, advocating for further exploration to harness the full potential of tuber crop skins in promoting sustainable circular agricultural practices.

Keywords: Agro-waste; Agricultural residues; Agricultural by-product; Sustainable resource management; Waste manage-ment; Nutrient recovery

1. Introduction

Sustainable agriculture has increasingly ascended to the forefront of international dialogue, commanding atten-tion from policymakers, researchers, and stakeholders across multiple sectors. The urgency of this discourse is propelled by a confluence of factors, such as; escalating global population, diminishing natural resources, and the exigencies of climate change. These factors all converging to demand a radical rethinking of how we man-age our food systems (Muhammad et al., 2019). Within this system, tuber crops such as potatoes, yams, cassa-va and taro occupy a critical aspect. These crops are more than mere dietary staples in numerous cultures; they are pivotal contributors to caloric and nutritional sustenance, effectively acting as essentials in global food se-curity (Scott, 2021; Zierer et al., 2021). However, amid the extensive research landscapes addressing cultivation practices Dahal et al. (2019), disease resistance Lastochkina et al. (2020) and Lal et al. (2021), and nutritional pro-files of these crops (Rinaldo, 2020), there exists a somewhat neglected domain: the sizable waste generated from tuber skins. A considerable proportion of these skins are discarded or underutilized, often being relegated to low-value applications such as animal feed or, worse, landfill deposits (Sampaio et al., 2020; Wang et al., 2020a; Kayiwa et al., 2021; El-Sawi et al., 2023). This current model of disposal or limited use is economically suboptimal and ecologically unsustainable. It amplifies waste management challenges and intensifies the environmental footprint of agricultural operations. Even more disconcerting is that this dismissal of tuber crop skins overlooks their latent value. Preliminary studies have indicated that these skins are endowed with valuable nutrients and bioactive compounds such as antioxidants and phenols (Wang et al., 2020b). These elements could find applications in diverse sectors, ranging from food fortification to pharmaceuticals and even cosmochemical. This transformation converts what is currently considered 'waste' into a high-value commodity.

The indiscriminate disposal of tuber crop skins constitutes not merely a loss of potential value-addition but also worsens the environmental load by contributing to environmental degradation (El-Sawi et al., 2023). This directly contradicts the objective of circular agriculture, which advocate for a zero-waste, involving a closed-loop system that optimally utilizes all agricultural outputs (Sarwono, 2023). In this sort of paradigm, waste from one process becomes input for another, thereby maximizing resource efficiency, reducing environmental degradation, and fostering economic stainability (Cainelli et al., 2020). Despite its conceptual appeal and practical merits, circular agriculture as applied to tuber crop skins remains an under explored area of inquiry. This limited exploration creates a research gap that is both timely and significant. Addressing this gap does not just contribute to theoretical understandings of sustainable agriculture; it has profound implications for practice and policy, offering a multifaceted solution to challenges of waste management, resource utilization, and environmental conservation.

Consequently, the overarching objective of this study is to present a comprehensive evaluation of the prospects and modalities for integrating tuber crop skins into circular agricultural systems. By doing so, this study aims to highlight both the untapped potential and the practical methodologies for leveraging these crop by products. It views them as valuable resources rather than waste. This approach contributes a novel dimension to the do-main of sustainable agriculture literature.

Scope of the study

The scope of the study is defined to offer both a comprehensive and focused examination of the utility of tuber crop skins in the context of circular agriculture, concentrating on four principal tuber crops: potatoes (*Solanum tuberosum*), yams (*Dioscorea spp.*), cassava (*Manihot esculenta*), and taro (*Colocasia esculenta*). These crops were specifically chosen for their global ubiquity and significant contribution to food systems. Their variances in biochemical composition make them robust case studies for a diversified yet targeted analysis. Although oth-er tubers exist, the focus on these four aims to lay a foundational understanding that could be inferred or adapted for other tuber varieties in future scholarly endeavours. In terms of geography, this review adopts a global perspective, by not placing emphasis on only regions where these crops are either staple foods or hold substantial economic significance.

Objective of the study

The primary goal of this study is to comprehensively evaluate the current state of research related to the utilization of tuber crop skins in the context of circular agriculture. To accomplish this, the study is guided by the following specific objectives:

•**To identify existing research on the utilization of tuber crop skins:** The first objective seeks to compile and assess the existing body of literature that discusses the various uses of tuber crop skins. This includes but is not limited to their nutritional profile, bioactive components, and current applications in food, pharmaceuticals, or other industries.

•**To assess the feasibility and efficiency of integrating tuber crop skins into circular agriculture practices:** This objective aims to evaluate how these uses align with the principles of circular agriculture. Special attention will be given to studies or data that specifically explore three key areas: the reduction of waste, optimization of resource use, and enhancement of economic benefits. This focus applies when integrating tuber crop skins into circular models.

•**To highlight gaps and future research needs:** Finally, this objective is geared towards identifying areas where existing research is lacking, inconclusive, or contradictory. Through a systematic analysis of the literature, this review will highlight gaps in current knowledge and propose avenues for future scholarly work.

Motivation of the study

The need for scholarly inquiry into waste minimization and value augmentation in tuber crops is motived by multiple intersecting trends. Foremost among these is the escalating concern over food waste as a key driver of environmental disorder, manifest in soil degradation, water resource misallocation, and greenhouse gas emissions (Pang et al., 2020; Redlingshofer et al., 2020; Shalini and Raghavan, 2021). This urgency is underscored by a rapidly increasing global population, which heightens the demand for food (Ojuederie et al., 2019; Mahapatra et al., 2022). At the same time, it intensifies the imperative for sustainability across the entire agricultural value chain. Tuber crops such as potatoes, yams, cassava, and taro, occupy a central role in this dialogue, given their substantial contributions to food systems in both developed and developing nations (Neela and S, 2019; Tadele, 2019). Despite their significance, a clear research deficit exists regarding the waste of tuber skins. These discarded byproducts contain untapped economic and nutritional potential. Their rich profiles of nutrients and bioactive compounds are amenable to diverse applications, ranging from food fortification to pharmaceutical interventions (Elhassaneen et al., 2016; Asharuddin et al., 2017; Fernandez et al., 2020; Mulia et al., 2023). Against this backdrop, circular agriculture emerges as an innovative and pragmatic framework for transforming these challenges into opportunities by promoting a zero-waste, resource-efficient agricultural paradigm (Velasco et al., 2022). However, current literature is disproportionately skewed toward macro-level strategies in circular agriculture. This includes practices such as crop rotation and manure management, leaving an academic void specific to the utility of tuber crop skins (Sui et al., 2018; Moretti et al., 2020). As a result, this study seeks to fill this gap by focusing on the skins of selected key tuber crops. The aim is to elucidate hitherto underexplored avenues for waste mitigation and value optimization. Hence, offering empirical and theoretical substantiation to their integration into a more resilient and sustainable circular agricultural ecosystem.

Significance of the study

This study marks a significant stride in sustainable agriculture by redefining the utilization of tuber crop skins within a circular agricultural model. It challenges the conventional perception of these skins as mere waste, uncovering their overlooked potential. Focusing on globally significant tubers like potatoes, yams, cassava, and taro, the study showcases their complex biochemical profiles, revealing a wealth of untapped value. The de-tailed examination of their nutritional and bioactive properties opens a variety of applications beyond their current limited use. This bridges the gap between academic research and practical implementations in food fortification, pharmaceuticals, cosmeceuticals, among others. As a result, this aligns with the progressive trends in circular economy practices, positioning the study at the forefront of sustainable agricultural innovation. By emphasizing circular agriculture specifically in the context of tuber crop skins, the study contributes a novel perspective to the literature, advocating for sustainable, zero-waste agricultural methods. It identifies key gaps in existing research, setting the stage for future exploration, and offering new insights into waste reduction and value augmentation in tuber crops. Therefore, the implication of the study extends beyond academia, resonating with the urgent need for sustainable agricultural practices in the face of escalating global food demands. It proposes a transformative approach, suggesting a shift from traditional waste management to a model in which tuber crop skins are recognized as valuable resources. Thus, this study not only fills a critical academic gap but also serves as a drive for policy and practical shifts towards more sustainable, economically viable agricultural systems.

The remainder of this paper is divided into 5 sections. Section 2 delineates the methodological approach employed for the Systematic Literature Review (SLR). In Section 3, we delve into a comprehensive review and synthesis of the pertinent literature. Section 4 is dedicated to presenting and discussing the principal findings of the study. The limitations of the study are critically examined in Section 5. Finally, the paper culminates with conclusions in Section 6.

2. Materials and method

To explore the underutilized potential and multifaceted applications of tuber crop skins within the context of circular agriculture, our inquiry is anchored by a Systematic Literature Review (SLR) methodology. This methodological choice is predicated on the SLR's proven efficacy in rigorously collating, scrutinizing, and synthesizing insights across a broad spectrum of scholarly literature. As a result, ensuring a comprehensive and unbiased assessment of the complex issues surrounding the utilization of tuber crop skins. Focusing on key crops such as potatoes, yam, cassava, and taro, our SLR aims to showcase the myriad potential of these often-discarded tuber crop skin within the confines of circular agriculture. By collating and dissecting this body of academic works, our SLR not only elevates the scholarly rigor but also serves as a crucial aspect in the evolving discourse on circular agricultural practices and resource-efficient food systems.

Article selection method

In our rigorous pursuit of exhaustive literature pertaining to the utilization of tuber crop skins in circular agriculture, we employed a dual-database search strategy, involving Web of Science (WoS) and ScienceDirect. Recognizing WoS's strength in multidisciplinary research coverage and ScienceDirect's reputation for its expansive collection of high-quality academic works Abioye et al. (2021), this binary approach facilitated a comprehensive extraction of scholarly articles directly relevant to our research query. Operating within the stringent parameters set by PRISMA guidelines Page et al. (2021), as showed in Fig. 1, we un-

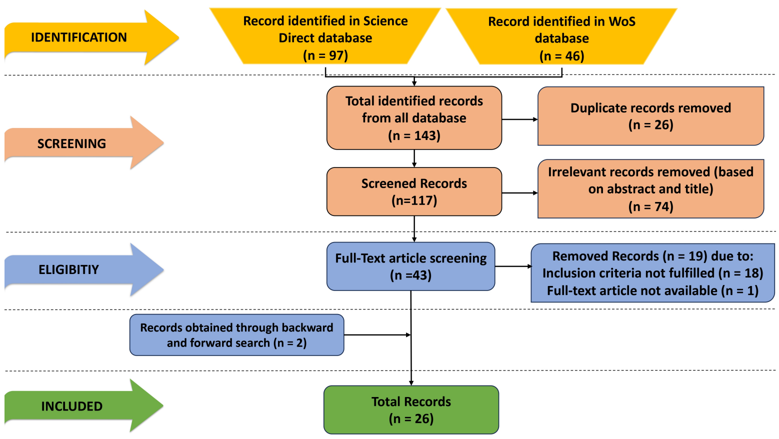

Figure 1. Flowchart of the systematic review process.

dertook the systematic review, ensuring both clarity and breadth in our findings. Given the dynamic landscape of circular agriculture and sustainable resource management, we focused our review on articles published between 2020 and 2023. This approach was to secure the most current perspectives and innovations concerning the utilization of skins from tuber crops like potatoes, yams, cassava, and taro. Also, recognizing that circular agriculture is an evolving field influenced by emerging technologies, policy shifts, and societal attitudes, this time frame guarantees that our study encapsulates the latest trends, challenges, and opportunities. Keywords steering our search included phrases such as ”tuber crop skins,” ”yam skins,” ”cassava skin,” ”potato skins,” ”taro skins,” “circular agriculture,” ”sustainable farming,” ”resource optimization,” ”waste reduction,” and ”value addition.” These search terms were used in various combinations to retrieve the most relevant articles. Furthermore, to uphold the scholarly rigor of our review, stringent inclusion and exclusion criteria were established. Five specific inclusion metrics were defined to focus our review on articles that precisely align with our research objectives. Meanwhile, four exclusion metrics served to filter out studies that were either tangentially related or did not meet academic quality standards.

Inclusion and exclusion criteria

To ensure the highest relevance and academic rigor in our study focusing on the utilization of tuber crop skins in circular agriculture, we meticulously crafted our selection parameters. Each chosen article had to meet all the inclusion criteria while avoiding any features that would place it under the exclusion benchmarks.
This rigorous approach ensures that the selected studies precisely illuminate the potential utilization of tuber crop skins. It focuses specifically on potatoes, yams, cassava, and taro within the circular agricultural sphere. Through this, we aim to fill the existing gaps in the literature, offering insights into how these often-overlooked tuber crop skins can contribute to both waste reduction and value addition in sustainable agriculture. Table 1 highlights the various predefined inclusion and exclusion criteria.
By explicitly stating these criteria, the study aims to eliminate biasness in article selection and ensure that only high-quality and relevant research is included in the review. This enhances the credibility and reliability of the findings and offers a pathway for potential replication and extension of the study.

Selected articles

Upon applying our carefully selected keywords and phrases, we initially gathered 143 publications: 97 from ScienceDirect and 46 from WoS, pertaining to the utilization of tuber crop skins in circular agriculture. After eliminating 26 duplicates, 117 articles remained for rigorous scrutiny. Our first-level screening involved a thorough examination of titles and abstracts. This led to the exclusion of 74 articles that did not directly address the opportunities and challenges of incorporating tuber crop skins. This specifically refers to the skins of potatoes, yams, cassava, and taro into circular agricultural systems. Upon delving into the full texts of the remaining 43 articles, 18 failed to meet our stringent inclusion criteria, while 1 was inaccessible. This systematic selection pro-cess cut our number of studies down to 24 relevant articles. To ensure exhaustive coverage, we utilized both backward and forward search techniques Wolfswinkel et al. (2013) and John et al. (2023), adding another 2 relevant articles to our collection. Consequently, our SLR consists of a curated selection of 26 journal articles that clearly align with our rigorous inclusion and exclusion benchmarks.

Review on the utilization of tuber crop skins in circular agriculture

Utilization of tuber crop skins has surfaced as an innovative avenue within the rapidly growing field of circular agricul-

Table 1. Summary of the inclusion and exclusion criteria.

Inclusion Criteria		Exclusion Criteria	
Consideration	Description	Consideration	Description
Relevance to research objectives	Articles must focus on the utilization of tuber crop skins in the context of agriculture, specifically within the scope of circular or sustainable models	Irrelevance to objectives	Articles not focusing on the skin of tuber crops or circular agriculture will be excluded
Peer-reviewed publications	Only articles published in peer-reviewed journals will be considered, as they generally meet higher quality standards	Non peer-reviewed materials	Grey literature, opinion pieces, and non-peer-reviewed publications will be excluded
Language	Articles published in English will be included to ensure accurate interpretation and analysis	Non-English publications	Articles published in languages other than English will be excluded due to potential interpretation challenges
Methodological rigor	Studies must exhibit methodological rigor, including clear research designs, methodologies, and evidence-based conclusions	Out of scope	Articles that are not focused on the any of the four tuber crop skins (i.e., yam, cassava, potato & taro)
Interdisciplinary perspectives	Articles from a range of disciplines including agriculture, environmental science, and sustainability will be considered to provide a multifaceted perspective		

ture. As a result, a plethora of research investigating its applicability in diverse sectors such as animal husbandry, bioenergy, waste management, pharmaceuticals and food applications have been undertaken. As the body of literature proliferates, a comprehensive examination is essential to reconcile the diverse and some-times divergent findings across these multiple domains. This section endeavours to synthesize relevant studies that illuminate the multi-dimensional utility of tuber crop skins. This involves critically evaluating both their promising contributions to sustainable development and any existing constraints or limitations. By dissecting the intricacies that define the role of tuber crop skins within the circular agriculture framework, this synthesis aims to offer researchers, agricultural practitioners, and policymakers a detailed perspective for future investigations and sustainable applications.

From waste to wealth: multidisciplinary applications of agricultural peels in circular agriculture

In the domain of circular agriculture, the valorization of yam peels and related biomass appears as a promising avenue for diverse applications, thereby contributing to waste minimization and resource optimization. Initiating the discourse, Aguihe et al. (2022) examined the egg-laying qualities of Japanese quails fed yam peel meal-based diets enriched with enzyme cocktails and yeast. Although their utilization of yam peel was minimal, their study showcases the feasibility of using fermented castor oil seeds to supplement poultry feed. This resultant outcome points toward the broader potential for utilizing alternative bio-resources in animal husbandry, involving yam peels. This idea aligns with circular agriculture's goal of closing the loop by reintegrating waste products back into the production system. A study by Amenaghawon et al. (2023) elevates this concept by employing machine learning models like artificial neural networks (ANN) and adaptive neuro-fuzzy inference systems (ANFIS) to optimize the biotechnological conversion of yam peels for citric acid production. This approach not only provides a sustainable route for waste valorization but also underscores the role of advanced computational methods in enhancing process efficiencies within a circular agricultural framework. In a related vein, Shao et al. (2022) delve into the extraction and purification of polysaccharides from Chinese yam peel, high-lighting their antioxidant and immunomodulatory properties. This suggests that waste products, often disposed, can have high-value applications in functional foods and pharmaceuticals. Onu et al. (2022) extends this circularity paradigm to the energy sector, using thermochemical pretreatment to prepare yam peel substrates for biogas production. Their utilization of machine learning algorithms, like ANN and ANFIS, for process optimization also provides an interdisciplinary approach in actualizing the objective of circular agriculture. The study underscores that the residues from biogas production could be applied as soil conditioners. Thereby bridging the agricultural loop. Li et al. (2021) takes another direction by focusing on the anticorrosion properties of yam peel constituents. This eco-friendly approach towards corrosion prevention has broader implications in reducing the industrial reliance on synthetic chemicals. Thus, offering an avenue for the circular use of agricultural waste for industrial applications.

Again, in the growing field of circular agriculture, the valorization of potato peel waste (PPW) has also emerged as a focal point for researchers who seek to create sustainable and valuable bio-products. With an increasing awareness of the principles of circular economy and the pressing need to mitigate environmental impact, sever-al ground-breaking studies have shed light on how PPW can be upcycled into myriad applications. This encompasses applications ranging from animal feed to green energy, and from waste remediation to functional fillers for food packaging. A study by Almeida et al. (2023) elucidate the paradigmatic shifts required for the valorization of potato peels within the circular economy framework. They offer an in-depth evaluation that sets the stage for subsequent research endeavors. Their work serves as an essential backdrop for understanding the multifaceted potential of PPW, particularly in the extraction of bioactive compounds and as a source of renewable energy. Nemadziva et al. (2022) further expand the horizon by studying the catalytic utilization of PPW for the enzymatic synthesis of bioactive compounds such as phellinsin A. This synthetic approach showcases the utility of PPW as a biotechnological raw material, linking it to health and pharmaceutical applications (another avenue where waste could be repurposed in a circular economy). Concurrently, Saeed et al. (2022) showcases the antioxidant capacity of potato peel extract, underlining its efficacy in stabilizing sunflower oil (a daily consumable prone to oxidative spoilage). This study notably correlates with the principles of circular agriculture by targeting food preservation through waste-derived natural additives. Thus, reducing the necessity for synthetic, often non-biodegradable chemicals. Shifting the lens to green chemical engineering, Daimary et al. (2022) conducted a comprehensive study on the thermochemical conversion of PPW into bio-oil and biochar. The biochar, enriched with alkali and alkaline elements, was subsequently calcined to serve as a heterogeneous catalyst for biodiesel production. This approach stands as a cornerstone in illustrating how circular agriculture could inter-sect with green chemistry to mitigate waste while generating energy. Importantly, their research offers an innovative yet practical pathway for the transformation of a single agricultural by-product into multiple value-added materials, embodying the very essence of circular agriculture.

Shifting the focus on taro peel starch (TPS) into the central theme of circular agriculture has further manifested the potential of how plant-based waste materials can contribute to sustainability. This is showcased by the study conducted by (Bidari et al., 2023). They explored the innovative use of taro peel starch as a renewable material for creating biodegradable films. This pioneering work employs response surface methodology (RSM) to optimize the film's physico-mechanical and water barrier properties. Consequently, their work demonstrates the potential of TPS in replacing petroleum-based components in plastic films. The films exhibited significant attributes such as positive linear effects in thickness, opacity, and water vapor permeability. Moreover, the films showed complete degradation in simulated environmental conditions. Some of which include river water and composting soil, within just five days, signalling its potential as a sustainable alternative for food packaging. When viewed through the lens of circular agriculture, this study complements existing literature by expanding the scope of plant-based waste utility. Also, like potato peel waste, taro peel waste has shown its potential to serve as a bio-based feedstock for sustainable applications. Moreover, the biodegradable films made from TPS underscore the aim of circular agriculture by reducing waste, lowering reliance on non-renewable resources, and contributing to ecological sustainability. As the film degrades quickly, it can be reincorporated into the natural environment, thereby closing the loop in the product life cycle.

The potential of cassava peel has gained notable recognition within the context of circular agriculture, emerging as a prominent sample of tuber skin utilization. For instance, the study by Aladegboye et al. (2022), which explores the use of cassava peels as an asphalt binder, sees a cross-sectional collaboration between civil engineer-ing and agricultural waste management. The study adds a new dimension to the use of agricultural residues, suggesting cassava peels as a sustainable binder in asphalt production. Thus, reducing the reliance on petroleum-based products. Advancing the discourse, the study by Aisien and Aisien and Aisien (2020), used cassava peels to pro-duce biogas, serving as an alternative source of renewable energy. In the context of circular agriculture, this suggests a seamless transition from food production to energy generation without incurring waste. Again, the study by Ospino et al. (2022) delve into the utilization of cassava peels for the synthesis of activated carbon. This study capitalizes on the porous structure and high carbon content of cassava peels, re-engineering waste into a cost-effective and efficient material for energy storage devices. In the same vein, Echesi et al. (2022) found that cassava peels can be used as a substrate for pectinase production. Therefore, showcasing its usability in various industrial applications, such as juice extraction and textile processing, thus keeping the agricultural waste in a continuous loop of utility. Contributing to the discourse on bioenergy, Osemwengie et al. (2020) high-lighted the use of cassava peels for bioethanol production. Their work presents how this agricultural by-product can be a multifaceted player in the bioenergy sector. Meanwhile, studies by Mourao et al. (2021) and Phetrungnapha et al. (2023) elevate cassava peels from a simple waste material to a complex bioresource capable of yielding polyhydroxybutyrate (PHB) and adsorbents for free fatty acid removal from waste cooking oil, respectively. The former demonstrates the high commercial value of PHB as a biomaterial, while the latter suggests a novel application for cassava peels in the purification of waste cooking oil. Hence, reinforcing the cyclical na-ture of agricultural waste usage. Continuing this narrative, Kumar et al. (2021) demonstrated the utility of cassava peels as a coagulant aid for institutional wastewater treatment. The techno-economic analysis (TEA) provided by the authors indicates that not only is this approach efficient but also economically viable. Finally, the study by Pulungan et al. (2020) bridges the gap between waste management and material science by optimizing the production of biodegradable plastic from cassava peels. This particular application revolutionizes how we view plastics and their impact on the environment.

In general, the emerging domain of circular agriculture, the diversified valorization of agricultural byproducts such as yam peels, potato peel waste (PPW), taro peel starch (TPS), and cassava peels are attaining academic and industrial attention for their profound implications on sustainability (Oghenejoboh et al., 2021; Khanal et al., 2023; Yafetto et al., 2023). The collective work of studies elucidates a multidimensional approach to agricultural waste. This ushers its role from mere dispose to that of a resource capable of complementing energy, feed, healthcare, and material science sectors. Groundbreaking computational methods, chiefly artificial neural net-works and adaptive neuro-fuzzy inference systems, are deployed for optimizing biotechnological conversion processes, exemplifying a transdisciplinary mesh between computer science and agriculture. In animal husbandry, waste such as yam and potato peels have shown viability as enriched feeds, offering a sustainable alternative to conventional feedstocks. The potential of these byproducts in producing high-value compounds: antioxidants, polysaccharides, bioactive compounds, and even coagulants for wastewater treatment establishes a precedent for their inclusion in pharmaceuticals and healthcare. Biodegradable films from TPS and plastics from cassava peels point towards an eco-friendly shift in material science. Hence, resonating with circular agriculture's objective of reducing waste and environmental impact. Furthermore, the use of byproducts like PPW and cassava peels for bioenergy production illuminates a pathway to renewable energy solutions. Additionally, another significant aspect of these studies resides in their ability to harmonize waste valorization with contemporary technological advancements. As a result, they foster a sustainable loop that synergies waste management, resource optimization, and ecological stewardship. The predominant narrative promotes a paradigm shift, encouraging a transition from linear to circular agricultural models. This underscores the imperative to shift our perspective on waste, seeing it not as an endpoint, but rather as the inception of new cycles that offer utility and foster the creation of value. Table **??** presents an overview of the salient findings derived from the relevant studies.

Statistical analysis

In our comprehensive scrutiny of the multifaceted applications of tuber crop skins in circular agriculture, we examined 26 empirical studies, classifying them into five salient thematic clusters: animal husbandry, bioenergy production, material science, wastewater treatment, and food applications. A significant focus was observed in material science, with 10 studies highlighting a keen interest in leveraging tuber crop skins in sustainable material development. This was followed by six studies in the bioenergy sector, reinforcing the growing emphasis on renewable energy sources within the context of circular agriculture.

Table 2. Summary of the relevant literature on the utilization of tuber crop skins in circular agriculture.

Authors names	Tuber crop skin	Area of circular utility	Key findings
(Aisien and Aisien, 2020)	Cassava	Bioenergy production	Cassava peels waste, mixed with cow dung, demonstrated feasibility for biogas and biofertilizer production. The study found that pretreatment with NH^4Cl led to the best biogas and methane yield. The digester sludge post-digestion exhibited promising biofertilizer qualities, highlighting cassava peels' potential in sustainable energy and fertilizer production.
(Candra et al., 2020)	Cassava	Food applications	The study examined the physicochemical properties of three cassava varieties and their suitability for diet snack chips. Variations in peel thickness crude fiber, and ash content were significant. Sensory tests showed Pacar cassava peels were preferred for their crispiness and taste, underscoring their potential in diet chip production.
(Oladele et al., 2020)	Cassava	Material science	Chemically treated palm kernel shell fiber (PKSF) and particulate cassava peel (PCP) enhanced epoxy composites' mechanical properties and wear resistance. Specifically, composites with 6% PCP exhibited increased stiffness and deformation resistance, showcasing cassava peel's viability as a sustainable reinforcement in composite production.
(Pulungan et al., 2020)	Cassava	Material science	The study optimized the production of biodegradable plastic from cassava peel starch. It identified optimal conditions for drying temperature and duration, resulting in a bioplastic with good mechanical properties and biodegradability. The research highlights cassava peel's potential as a sustainable source for bioplastic production, offering an eco-friendly solution to plastic waste.
(Azizi et al., 2021)	Potato	Food applications	The study showcased the development of an optimized potato snack using potato skins, achieving dual objectives: minimizing food waste and providing a healthier snack option. This innovation highlights the potential of potato skins in producing sustainable, nutritious food products, emphasizing their value in eco-friendly and health-oriented food solutions.
(Castro et al., 2021)	Cassava	Material science	The study produced polyhydroxyalkanoates (PHAs) from cassava peel waste using Cupriavidus necator, identifying optimal pro-duction condition the biopolymer was then transformed into microfibers via electrospinning, showcasing cassava peel waste's innovative application in biopolymer manufacturing, with potential industrial and biomedical uses.
(Kumar et al., 2021)	Cassava	Wastewater treatment	Cassava peel starch (CPS) was evaluated as an eco-friendly coagulant for institutional wastewater treatment. The study optimized the treatment process using CPS and found it to be economically viable with significant removal efficiencies for turbidity, TSS, and COD. CPS proved to be a sustainable alternative to chemical coagulants, with potential to contribute to wastewater management and pollution reduction.
(Li et al., 2021)	Yam	Material science	Chinese yam peel extracts (CYPE), containing diosgenin, batatasin-I, batatasin-III, and yam polysaccharide, effectively prevent copper corrosion in artificial seawater. Acting as mixed-type inhibitors with mainly anodic effects, CYPE's high efficiency at elevated temperatures positions it as a potential eco-friendly solution for protecting copper in marine settings.
(Mourao et al., 2021)	Cassava	Material science	Using cassava peel hydrolysate, Stigeoclonium sp. B23 produced polyhydroxybutyrate (PHB), a promising biomaterial, achieving 12.16% PHB content. Despite some toxicity in zebrafish embryos from PHB nanoparticles, the study highlights cassava peel as a renewable source for PHB production, presenting an alternative for biomaterial applications and tackling agro-industrial waste.
(Papathoti et al., 2021)	Cassava	Bioenergy production	The study focused on boosting ethanol production from cassava peel waste through alkali-assisted hydrothermal pretreatment. Using the thermotolerant Kluyveromyces marxianus, higher ethanol yields (0.44 g/g) and efficiency (86.11%) were achieved with simultaneous saccharification and fermentation (SSF) over separate hydrolysis and fermentation (SHF), highlighting cassava peel's viability as a bioethanol feedstock.
(Aguihe et al., 2022)	Yam	Animal husbandry	Feeding Japanese quails with diets including yam peel meal, enzymes, and yeast showed varied egg quality effects. Adding yam peel, FCSM, and methionine types improved health and productivity. Yet, high yam peel and FCSM levels (up to 150 g/kg) reduced carcass weight without harming other physiological traits. This indicates yam peel's potential in boosting egg quality, despite carcass weight considerations.
(Aladegboye et al., 2022)	Cassava	Material science	The study assessed Cassava Peel Ash (CPA) as an asphalt mixture modifier, focusing on sustainable pavement material development and agricultural waste reduction. Findings revealed that CPA concentrations notably affected the mixtures' volumetric properties, suggesting CPA's efficacy in improving asphalt performance.
(Daimary et al., 2022)	Potato	Bioenergy production	Potato peels were transformed into biochar, bio-oil, and a biodiesel catalyst, with peak yields of 23.60% bio-oil and 29.50% biochar at $500^{O}C$. The potassium-rich catalyst achieved a 97.50% oil conversion in biodiesel production, showcasing potato peels' sustainable conversion into valuable fuel and chemical products.

Continue of Table 2

(Ebrahimian et al., 2022)	Potato	Bioenergy production	The study outlined the valorization of potato peel waste (PPW) for producing biofuel, bioplastics, and biosorbents, showcasing its potential in sustainable bioproduct development via biological and thermochemical methods. This emphasizes PPW's importance in a PPW-based biorefinery approach.
(Haque et al., 2022)	Potato	Food applications	Ethanol-extracted antioxidants from potato peels showed 89.14% radical scavenging activity, presenting a natural solution for food preservation. Incorporating a 3% ethanol extract into nacho dough enhanced antioxidant activity, indicating a sustainable method to boost food product nutrition using potato peels.
(Min et al., 2022)	Potato	Material science	Potato skin carbon dots, used as nanofillers in gelatin-based packaging, enhanced the material's antioxidant and antimicrobial activities, water vapor permeability, hydrophobicity, UV-barrier properties, and mechanical stability. This underscores their potential as sustainable, value-added nanofillers for packaging uses.
(Nemadziva et al., 2022)	Potato	Material science	Potato peels were utilized to generate chlorogenic acid (CLA) and caffeic acid (CFA), which laccase converted into phellinsin A, boosting antioxidant capacity with low cytotoxicity. This indicates their potential as antioxidant agents across applications, highlighting potato peels' effectiveness in producing valuable bioactive compounds via laccase catalysis.
(Onu et al., 2022)	Yam	Bioenergy production	Optimizing yam peel thermo-chemical pretreatment for biogas through ANFIS, ANN, and RSM models showed ANFIS's superior accuracy. Optimal conditions led to a biogas yield with 92% methane. The research underscores yam peels' viability for biogas production and suggests using digestion sediments in agriculture.
(Ospino et al., 2022)	Cassava	Material science	The study involved producing activated carbon from cassava peels for use as electrode material in supercapacitors. The activated carbon, treated with potassium hydroxide and phosphoric acid, showed a specific capacitance of 64.18 F/g, indicating its viability as a cost-effective and sustainable electrode material for energy storage applications.
(Saeed et al., 2022)	Potato	Food applications	Potato peel extract, prepared with hexane, exhibited strong antioxidant activity, on par with synthetic antioxidants like BHA, in stabilizing sunflower oil. Sunflower oil enhanced with this extract showed increased oxidative stability, underscoring potato peel extract's potential as a natural antioxidant for extending vegetable oils' shelf life.
(Singh et al., 2022)	Potato	Wastewater treatment	Potato peel biochar outperformed potato peel powder in adsorbing chlorpyrifos, achieving a 72.06% removal efficiency. This highlights the potential of potato peel waste as an economical and sustainable water treatment adsorbent.
(Shao et al., 2022)	Yam	Food applications	Optimized extraction of Chinese yam peel polysaccharide (CYPP) mainly yielded glucose and galactose. CYPP-1 showed antioxidant, immunomodulatory, and hypoglycemic effects, indicating its potential for functional food and pharmaceutical industries.
(Amenaghawon et al., 2023)	Yam	Bioenergy production	Using yam peels with EDTA (0.3 g/l) and coconut oil (5.0% w/w) significantly boosted citric acid production by 49.1%, achieving 43.08 g/l. This showcases the yam peels' biochemical potential when combined with specific stimulants, although sodium fluoride lacked a stimulatory effect. The study reveals yam peels' promising role in citric acid bioproduction.
(Bidari et al., 2023)	Taro	Material science	Taro peel starch (TPS) was used to create biodegradable films via casting, with optimized TPS and glycerol levels impacting film characteristics. These TPS films, exhibiting an amorphous-type crystallinity, fully degraded in 5 days under environmental conditions, confirming their viability as sustainable food packaging polymers.
(Goyi et al., 2023)	Potato	Wastewater treatment	Potato peel hydrochar, created via hydrothermal carbonization, demonstrated enhanced Congo red adsorption over raw potato peel powder. This highlights its viability as a sustainable water treatment adsorbent, aligning with pseudo-second-order kinetics and Freundlich isotherm models.
(Phetrungnapha et al., 2023)	Cassava	Wastewater treatment	Cassava peel-derived adsorbent effectively removed free fatty acids from waste cooking oil. The optimal adsorbent, developed through calcination and NaOH modification, demonstrated high adsorption capacity and was characterized using FT-IR and SEM. The study revealed that this adsorbent is a promising, sustainable solution for purifying waste cooking oil, highlighting cassava peels' utility in environmental remediation.

3. Results and discussion

In this section, we offer a comprehensive synthesis of pivotal findings derived from rigorously peer-reviewed scholarly contributions focused on the utilization of tuber crop skins in circular agriculture. Each selected manu-script was subjected to a meticulous content analysis that employed advanced statistical methods to unveil emerging trends and discernible patterns within this multifaceted field. Alongside quantitative inquiries, an exhaustive qualitative review was carried out to highlight detailed thematic dimensions embedded in the existing body of work. Expanding upon these diverse lines of analysis, we elucidate the multifunctional utility of tuber crop skins in various sectors such as food application, bioenergy production, animal feed supplementation (animal husbandry), material science and wastewater treatment applications. This analytic framework serves as a lens to unpack the intricate interconnections and contributing factors that underlie the role and valorization of tuber crop skins within the circular agriculture paradigm.

Wastewater treatment and food applications were explored in four and five studies respectively, pointing to an evolving interest in these domains for environmental man-agement and culinary innovation. Notably, a single study addressed animal husbandry, suggesting a nascent yet promising area for further exploration. These categories out-line the current scope of research and underscore areas for future scholarly exploration. They offer insights into untapped potential and encourage a multidisciplinary ap-proach to circular agriculture. Fig. 2 graphically encapsulates these five pivotal thematic clusters.

Again, to further examine the evolving trend in the utilization of tuber crop skins within circular agriculture over time, we conducted a chronological analysis of academic publications. The time frame of this scrutiny extended from 2020 to 2023. During this period, there was a notable rise in the number of publications: starting with four articles in 2020, rising to six in 2021, and then further increasing to twelve studies in 2022, before experiencing a decrease to four by the third quarter of 2023. This dynamic pattern may be indicative of several underpinning factors. The modest beginnings in 2020 possibly reflect the growing stage of this research avenue. The spike in 2022 could signify an academic recognition of the urgency for sustainable agriculture, particularly in the wake of increasing environmental concerns. Conversely, the dip in 2023, despite being only partial data for the year, may point towards a shift in research concentrations or possibly a period of academic digestion and integration of existing studies. This temporal examination deepens our understanding of the evolving landscape of this field. Furthermore, it highlights the growing importance of utilizing tuber crop skins within the broader contexts of circular agriculture and sustainability.

Additionally, our study aimed to clarify the geographical spread of scholarly research on the utilization of tuber crop skins in circular agriculture. Our analysis identified empirical works from 14 nations, with a predominant focus on Africa, South America, and Asia. Intriguingly, Asia accounted for a significant portion of the research collection. This trend may be linked to the region's growing dedication to agricultural sustainability and technological innovation. Africa followed closely in significance, with a notable presence in the research. This may be indicative of the continent's increasing emphasis on sustainable agricultural practices as a means to address persistent challenges such as food insecurity and climate change adaptation. In contrast, South America's involvement lagged behind both Asia and Africa. This could signify either an early stage of scholarly inquiry in the region or a comparatively lesser emphasis on tuber crop skins in the broader scope of agricultural research. Remarkably, an evident absence of research contributions was noted from Europe, Australia and North America. This void is particularly striking given these regions' advancement in agricultural technologies and sustainability paradigms. The dearth of academic output from these continents suggests a couple of possibilities. Firstly, it could indicate that the theme of tuber crop skin utilization in circular agriculture has not yet gained substantial traction in academic discourse within these regions. Secondly, it may reflect that other priorities in agricultural sustainability are currently taking precedence over this specific area of focus. This geographical gap in academic contributions

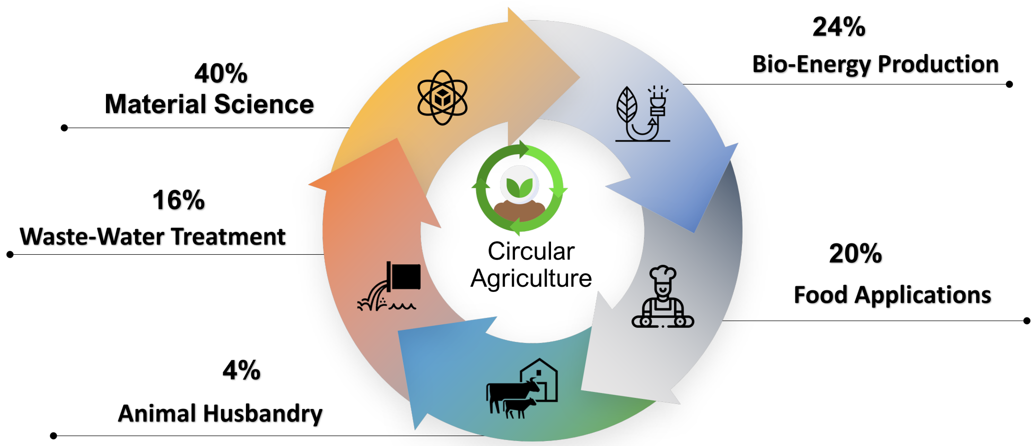

Figure 2. Utilization of tuber crop skin in circular agriculture.

adds complexity to our understanding, highlighting areas of deficiency that present opportunities for future scholarly research. This geospatial analysis provides a comprehensive overview of current academic trends and raises important questions about the disparity in scholarly activity across different continents. Fig. 3 captures this geographical diversity, thereby enriching our overall understanding of the global research landscape in this specialized domain of circular agriculture.

Multifaceted applications of tuber crop skins in circular agriculture

The use of tuber crop skins in circular agriculture has garnered considerable attention from both the academic and industrial sectors. This has led to a multidisciplinary dialogue involving agronomists, environmental scientists, and policymakers. In this section, we presents a comprehensive synthesis of existing research, examining the versatile applications of tuber crop skins in the field of circular agriculture. Based on a detailed analysis of the relevant peer-reviewed articles, the study affirms the considerable potential of tuber crop skins as sustainable resources for a variety of sectors. These skins find application across various sectors, including animal husbandry, bioenergy production, material science, wastewater treatment, and food applications. These skins have proven to be invaluable, serving as nutrient-rich feed in animal husbandry and as promising feedstocks for bioenergy production. Their high content of cellulose, hemicellulose, and lignin offers groundbreaking opportunities in material science. Additionally, their absorptive properties present viable solutions for wastewater treatment. Moreover, their nutrient-dense profiles are well-suited for food fortification and the creation of functional foods. This comprehensive assessment seeks to present a detailed overview of the scope and distribution of tuber skin applications across the identified sectors, as presented in Table 3.

Implication and recommendation of the multifaceted applications of tuber crop skin in circular agriculture

The multifaceted applications of tuber crop skins within circular agriculture systems present a promising avenue for sustainable resource management, energy production, material innovation, and food security. This section outlines the implications and recommendations stemming from the utilization of these agricultural by-products across various domains. From enhancing animal husbandry practices and advancing bioenergy solutions to pioneering in material science innovations and unlocking nutritional potential in food applications, tuber crop skins are an untapped resource with considerable environmental and economic benefits. This section highlights and discusses issues, solutions, and implications regarding the use of tuber crop skins, while also suggesting areas for further exploration.

Sustainable animal husbandry

Exploring the use of tuber crop skins in animal husbandry presents a promising solution within the framework of circular agriculture. These skins, rich in essential nutrients like carbohydrates, fibers, and minerals, offer a sustainable alter-native to conventional animal feedstocks such as corn and soy, potentially reducing reliance on resource-intensive feeds (Rahman et al., 2021; Okike et al., 2022; Rahmani et al., 2022). The inherent organic matter in tuber crop skins enhances livestock gut health and well-being, contributing to improved quality of animal-derived products (Wanapat et al., 2013; Ruqayyah et al., 2014). Furthermore, their fibrous nature provides environmentally friendly bedding materials, showcasing a multifaceted approach to sustainability (Omole et al., 2013; Gebrechristos and Chen, 2018). The potential health benefits from bioactive compounds in these skins, such as antioxidants, further posit an opportunity to enhance animal health and productivity (Surai, 2014; Oloruntola, 2020). This integration not only supports

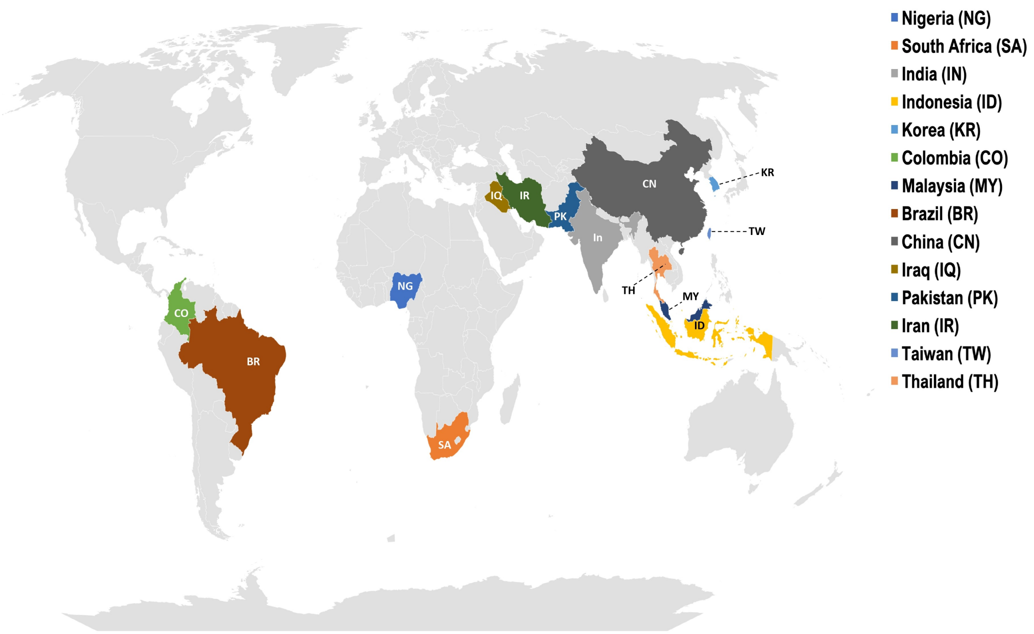

Figure 3. Regions of empirical investigation on the utilization of tuber crop skins in circular agriculture.

Table 3. Content analysis of selected articles showcasing the utilization of tuber crop skins in circular agriculture across var-ied domains.

Authors names	Animal husbandry	Bioenergy production	Material science	Wastewater Treatment	Food applications
(Aisien and Aisien, 2020)		✓			
(Candra et al., 2020)					✓
(Oladele et al., 2020)			✓		
(Pulungan et al., 2020)			✓		
(Azizi et al., 2021)					✓
(Castro et al., 2021)			✓		
(Kumar et al., 2021)				✓	
(Li et al., 2021)			✓		
(Mourao et al., 2021)			✓		
(Papathoti et al., 2021)		✓			
(Aguihe et al., 2022)	✓				
(Aladegboye et al., 2022)			✓		
(Daimary et al., 2022)		✓			
(Ebrahimian et al., 2022)		✓			
(Haque et al., 2022)					✓
(Min et al., 2022)			✓		
(Nemadziva et al., 2022)			✓		
(Onu et al., 2022)		✓			
(Ospino et al., 2022)			✓		
(Saeed et al., 2022)					✓
(Singh et al., 2022)				✓	
(Shao et al., 2022)					✓
(Amenaghawon et al., 2023)		✓			
(Bidari et al., 2023)			✓		
(Goyi et al., 2023)				✓	
(Phetrungnapha et al., 2023)				✓	

waste reduction and resource optimization but also aligns with the broader goals of circular agriculture by closing nutrient loops and enhancing the ecological footprint of livestock farming. Additionally, it offers socioeconomic benefits, particularly for smallholder farmers, by providing a cost-effective alternative to traditional feeds and bedding materials, thus enhancing economic resilience (Kalio et al., 2015). Despite the evident potential, there is a notable gap in empirical re-search focusing on this application, highlighting the need for comprehensive studies to assess the nutritional, health, environmental, and economic impacts of incorporating tuber crop skins into animal husbandry. This area represents a promising avenue for future research, with the potential to redefine conventional practices in animal husbandry by promoting more sustainable, integrated approaches within circular agricultural system.

Bioenergy innovation in with tuber crop skins

Within the circular agriculture frameworks, the conversion of tuber crop skins to bioenergy stands out as a key area of innovation. Tuber crop skins are increasingly recognized not just as agricultural waste but as valuable bioenergy feedstock for producing biogas, bioethanol, and biodiesel (Nair et al., 2022; Almuhayawi et al., 2023). The rich fibrous and starchy nature of tuber crop skins offers an abundant source of fermentable sugars (Okekunle et al., 2016; Awogbemi et al., 2022). This makes them ideal for bioenergy production processes. Anaerobic digestion yields methane-rich biogas, while fermentation processes produce bioethanol (Wu et al., 2016). Advances in pyrolysis and gasification have further expanded their use, facilitating the creation of syngas and bio-oil (Foong et al., 2023). The transformation of tuber crop skins into bioenergy aligns with sustainable energy goals, offering a renewable alternative to diminish reliance on fossil fuels. This shift not only addresses the pressing need for sustainable energy solutions but also integrates waste management into energy production, enhancing agricultural circularity (Awogbemi et al., 2022). The holistic use of tuber crop skins in bioenergy production exemplifies the circular economy's ethos, turning potential waste into valuable energy resources and contributing to environmental sustainability (Wu et al., 2016). The need for cross-disciplinary research and policy support is highlighted by this multifaceted approach. It is essential to unlock the full potential of tuber crop skins in bioenergy within circular agriculture. This promises a path towards energy security and environmental sustainability.

Material science innovations with tuber crop skins

The integration of tuber crop skins into material science represents a significant advancement within circular agriculture, offering a sustainable solution to the challenges of waste management and environmental degradation (Borah et al., 2017). Recognized for their rich cellulose, hemicellulose, and lignin content, tuber crop skins are becoming essential raw materials for developing bio-composites, bio-based plastics, and functional films (Bello et al., 2023). These applications not only enhance the mechanical properties and biodegradability of materials but also provide eco-friendly alternatives to synthetic plastics, aligning with efforts to reduce environmental pollution (Sugumaran et al., 2015; Versino et al., 2015; Charles et al., 2022). Further exploring their utility, the bioactive compounds in tuber crop skins are being harnessed for antimicrobial and antioxidant properties, making them ideal for food packaging that demands extended shelf life and microbial resistance (Miller et al., 2022; Thuppahige et al., 2023). Their application in aerogels and adsorbents for environmental remediation, targeting pollutants and heavy metals in wastewater, and even in energy storage devices like supercapacitors, showcases the breadth of their potential impacts (Osman et al., 2019; Nathan et al., 2021; Minisha et al., 2022; Odeyemi et al., 2023). This transformation of tuber crop skins from waste to valuable material science assets exemplifies the principles of the circular economy, emphasizing the creation of sustainable materials from agricultural by-products. The convergence of waste reduction, innovative material production, and environmental stewardship underlines the holistic benefits of leveraging tuber crop skins in circular agriculture. This shift necessitates focused research and supportive policy frameworks to fully exploit their sustainability potential, marking a pivot-al step towards realizing circular agricultural systems.

Wastewater treatment innovations with tuber crop skins

The role of tuber crop skins in wastewater treatment within circular agriculture systems presents an innovative approach to sustainable resource management (Bhatnagar et al., 2015; Kumar et al., 2017). These skins, abundant in organic matter such as carbohydrates and proteins, exhibit natural adsorptive properties for removing pollutants, offering a low-cost alternative to traditional adsorbents (Kumar et al., 2017; Asharuddin et al., 2018; Nahas et al., 2019; Rodriguez et al., 2021). Processed into biochar or activated carbon, tuber crop skins effectively eliminate a variety of contaminants, matching the efficiency of commercial adsorbents due to their high surface area and functional groups (Asuquo et al., 2018; Gale et al., 2021; Geca et al., 2022; Liang et al., 2015). Moreover, the enzymatic potential of tuber skins in biodegradation processes highlights their ability to act as biological catalysts, broadening the spectrum of treatable pollutants, including pharmaceuticals and synthetic dyes (Belcaid et al., 2023; Hoseinzadeh et al., 2014; Kayiwa et al., 2022). This dual functionality aligns with waste reduction goals and enhances water recycling in agriculture. It reinforces circular economy principles by enabling the reuse of treated wastewater for irrigation (Abdelraof et al., 2019). The underexplored potential of tuber crop skins in wastewater treatment emphasizes the necessity for in-depth research. This research should focus on standardizing treatment methods and maximizing efficiency. The goal is to integrate tuber crop skins more effectively into sustainable agriculture and environmental conservation efforts. Emphasizing their multifaceted utility in wastewater treatment reinforces circular agriculture's commitment to environmental and economic sustainability.

Nutritional innovations with tuber crop skins

In the aspect of circular agriculture, tuber crop skins offer more than just a solution for waste management; they play a pivotal role in food innovation, enhancing nutritional content and facilitating the development of functional foods (Samotyja, 2019; Vaitkeviciene, 2019; Triwidatin and Djuanda, 2023). These often-overlooked by-products, recognized for their rich composition of vitamins, minerals, fiber, and bioactive compounds like phenols and flavonoids, are valuable for enriching a variety of food products. From bakery goods to beverages and snacks, they showcase a sustainable approach to food production (Curti et al., 2016; Ben et al., 2017). The functional attributes of tuber skins, such as their antioxidant and colorant properties, provide natural alternatives to synthetic additives, enhancing food safety and nutritional profiles (Javed et al., 2019; Helal et al., 2020). Moreover, their starch and fiber content offers potential as natural thickeners or stabilizers in culinary applications, contributing to innovative food textures and consistencies (Rengsutthi and Charoenrein, 2011; Xie et al., 2018). Addressing global challenges like food security and malnutrition, the strategic use of tuber crop skins in food products underscores their societal and nutritional significance, especially in regions facing food scarcity (Alemu, 2020). The transformation of tuber skins into high-value products such as protein concentrates and dietary fibres on an industrial scale aligns with the goals of sustainable food systems (Caliskan et al., 2023). This process provides eco-friendly and economically viable alternatives (Singh et al., 2023). This comprehensive approach not only underscores the necessity of waste reduction and nutrient recycling but also positions tuber crop skins as a cornerstone of sustainable food production. The extensive benefits of tuber skins in food applications under-score the importance of continuous interdisciplinary research. This research should focus on standardizing extraction methods and quantifying bioactive compounds. The goal is to meet regulatory standards and consumer expectations, fully leveraging the potential of tuber crop skins in circular agriculture.

Summary and future research directions in the multifaceted utilization of tuber crop skins in circular agriculture systems

The diverse applications of tuber crop skins substantially enhance the landscape of circular agriculture. They impact crucial domains including animal husbandry, bioenergy production, material science, wastewater treatment, and food applications (Okike et al., 2015; Nair et al., 2022). The potent nutrient profiles, fibrous properties, and bioactive constituents of tuber crop skins enable their use in sustainable and innovative solutions (Hoseinzadeh et al., 2014; Charles et al., 2022). Tuber crop skins serve various roles, from nutritional supplements in animal feed to feedstocks for bioenergy, building blocks in bio-based materials, and agents in wastewater purification and food fortification. In each of these applications, they embody the essence of resource optimization and waste minimization. These are fundamental goals of circular agriculture. Despite the apparent robustness of these applications, the use of tuber crop skins in circular agriculture is still relatively underexplored and fragmented. A notable deficiency is the lack of interdisciplinary research that melds nutritional science, environmental sustainability, and economic modeling. Such integrated research is crucial for a comprehensive understanding of the impact and feasibility of these applications, as noted in studies by Kumar et al. (2021) and (Daimary et al., 2022). Empirical studies focusing on the long-term outcomes, scalability, and the Technological Readiness Level (TRL) of these utilizations are notably lacking. Moreover, research has not yet completely delved into the mechanisms underlying the bioactive properties of tuber crop skins. This includes understanding their roles in enhancing animal health, improving bioenergy conversion efficiency, and aiding pollutant sorption in wastewater treatment. In the area of food applications, quantifiable metrics for bioactive compounds, and regulatory compliance are largely undeveloped. Such limitations underscore the urgent need for robust, methodologically sound, and comprehensive studies to elucidate the complexities involved. Additionally, incorporating tuber crop skins into existing agricultural and industrial systems brings up issues related to supply chain logistics, quality control, and policy frameworks. These critical aspects are yet to be thoroughly addressed in the academic literature. Ethical considerations regarding resource allocation, especially in food-scarce regions, also warrant scholarly attention. Finally, the use of tuber crop skins offers a promising route to enhance the sustainability and functionality of circular agricultural systems. However, the field is at a critical juncture that calls for rigorous empirical research and collaborations among multiple stakeholders. It is through such focused endeavours that the full spectrum of opportunities afforded by tuber crop skins can be unlocked, actualized, and optimized for the future.

Limitations of the study

In reflecting upon the limitations of our study, it is important to acknowledge certain constraints that have influenced the scope and depth of our findings. Our study was primarily confined to publications from 2020 to 2023. While this time frame allowed for a focused review, it may have excluded both earlier foundational studies and very recent re-search. This potentially overlooks broader historical insights or cutting-edge developments in the field. Additionally, the geographical representation in the reviewed literature was uneven, potentially introducing a regional bias. This disparity might affect the interpretation of global trends in the utilization of tuber crop skins. Particularly, certain regions, especially those leading in research and application, could disproportionately influence the study's conclusions. Another limitation is our focus on studies published in English. This language restriction might have inadvertently excluded significant research in other languages. Consequently, narrowing the global perspective and understanding of innovations in circular agriculture involving tuber crop skins. There is also the potential for selection bias. Despite efforts for a comprehensive review, our selection criteria might have favored certain research methodologies or applications. This could result in overlooking divergent or contradictory views, leading to a somewhat restricted interpreta-tion of the current state of the field. Moreover, our reliance on academic databases (ScienceDirect and WoS) for sourcing articles means that our review is subject to publication biases and the predominance of certain journals. This could skew the representation of specific aspects of research in the utilization of tuber crop skins. Lastly, our focus predominantly on academic literature may not fully capture the practical advancements and challenges in the indus-try. Some innovative applications or real-world implementations of tuber crop skins in circular agriculture might not be extensively documented in scholarly articles. Recognizing these limitations is essential for properly contextualizing the study's findings. These constraints should be considered when applying our insights to future research, policy-making, or practical applications in the aspect of circular agriculture and sustainable use of agricultural by-products.

4. Conclusion

This study highlights the transformative role of tuber crop skins in circular agriculture, marking a shift toward sustain-able food production and resource management. The study has explored their multifaceted utility, from serving as nutrient-rich feed supplements in animal husbandry to emerging as valuable feedstocks for bioenergy production. In material science, their substantial cellulose, hemicellulose, and lignin content make them ideal for bio-composites and bio-based plastics. This aligns with the waste-to-resource ideology at the heart of circular agriculture. Their potential is further demonstrated in wastewater treatment and food applications, where they help treat pollutants and enrich food products, addressing global challenges such as malnutrition. However, despite these promising areas, there is a lack of comprehensive empirical research on the long-term environmental, technical, and economic implications of these applications. The study highlights this gap as a crucial area for future interdisciplinary research. Such research is necessary to fully realize the potential of tuber crop skins in a sustainable, economically viable, and resource-efficient agricultural paradigm. This study sets the stage for future explorations, advocating for an integrated approach to ad-dress these gaps. In doing so, it underscores the importance of tuber crop skins in advancing global sustainability goals and contributing to a restorative agricultural process.

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Authors contributions
Aziz Caliskan: conceptualization, methodology, visualization, writing-original draft preparation and Revising of manuscript; Norhidayah Abdullah: supervision, sunding acquisition, editing, visualization and proof-reading of manuscript; Noriza Ishak: supervision, methodology, visualization, validation and proof-reading of manuscript; Divine Senanu Ametefe: writing-original draft preparation, methodology, validation, editing and proof-reading of manuscript, visualization, validation and revising of manuscript; Imene Tatar Caliskan: curation of literature, methodology, validation, visualization, editing and revising of manuscript.

Availability of data and materials
The data that support the findings of this study are available from the corresponding author, upon reasonable request.

Conflict of interests
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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