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Toward sustainability in coconut processing: current challenges, emerging concepts, and circular solutions

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The global coconut industry plays a vital role in supporting the livelihoods of millions of people worldwide, predominantly in the Asia-Pacific region. Coconut is one of the most versatile and sustainable crops, as every part of it can be utilised for various purposes. There are many industries, apart from food and beverage, including cosmetics, healthcare, packaging, and many more, that rely on coconut as a raw material. Despite its potential, the coconut industry is associated with multiple challenges, such as high energy consumption, poor waste management, the use of outdated technologies, inefficient infrastructure, and the underutilization of by-products. Therefore, a holistic and collaborative approach is required to support and turn this vibrant industry into a sustainable one in the future. With this background, this review presents the current landscape of the coconut processing industry, identifies key technological challenges, and proposes sustainable strategies that will benefit the industry, its associated stakeholders, and the environment. Specifically, this article emphasises the role of resource efficiency, waste conversion, reduced chemical usage in industry, green substitutes, sustainable packaging solutions, social and economic responsiveness, and life-cycle analysis, which shifts these perspectives towards achieving and attaining the sustainable development goals. Additionally, this review underscores the need for stronger alignment between innovation and policy to help transform the current coconut-processing industry into a circular, low-carbon, and inclusive economy. Overall, the ideas presented aim to promote interventions that will create a resilient coconut supply chain for the future.

Sustainability spotlight

Globally, the coconut industry plays a vital role in supporting the livelihoods of millions. Despite its potential, current industry practices are associated with high energy consumption, waste mismanagement, the use of outdated technologies, infrastructure inefficiencies, and the underutilization of by-products. This necessitates a holistic and collaborative approach to developing sustainable solutions, and in turn, supports the growth of this vibrant industry. With this background, this review proposes sustainable strategies that will benefit the industry, its associated stakeholders, and the environment. In particular, this article emphasises the potential of resource efficiency, waste valorisation, reduced chemical use, green alternatives, sustainable packaging solutions, socio-economic responsibility, and life cycle assessment, directing the focus to sustainable development goals.

1. Introduction

The coconut palm (*Cocos nucifera* L.) is usually referred to as the "wish-fulfilling tree of heaven" or 'tree of life' due to its major role in the global agricultural landscape, supporting the livelihood, social, nutritional, health, and wellness security of millions worldwide, particularly in Asia and the Pacific regions. It has been reported that this industry provides nutrition to approximately 60 million households and employment to about 30 million farmers, both directly and indirectly, through activities involved in the cultivation, harvesting, distribution, marketing, and processing of coconut and husk-based products, as well as eco-tourism.[1] Coconut farming supports farmers globally by providing a sustainable source of income, food, and employment, as well as opportunities for tourism and trade, with millions of smallholder farmers relying on coconut cultivation as their primary livelihood.

Coconut is cultivated and commercially exploited across the tropical belt of Asia, East Africa, and the Americas, covering approximately 12 million hectares in more than 90 countries, and is consumed by people in more than 110 countries worldwide.[2]

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Indonesia, the Philippines, India, Brazil, Sri Lanka, Thailand, Vietnam, Malaysia, Papua New Guinea, and Tanzania are the top ten coconut-producing countries, collectively accounting for 91% of global production.[3] The global coconut market is projected to reach $30 billion by 2026, driven by a compound annual growth rate (CAGR) of 13.6%, representing an estimated revenue increase of $19.7 billion between 2018 and 2026.[4]

Coconut, a fibrous drupe, is highly versatile, with all its components, water, kernel, husk, and shell used to develop a diverse range of food, non-food, and industrial products. Its nutritional benefits and sustainability value underline its importance in international marketplaces. Indeed, from top to bottom, every part of the coconut tree has income-generating potential, serving as a very central source of food, drink, medicine, fibre, timber, and fuel, as well as raw materials for various commercial products. In the context of food applications, coconut water, the sweet liquid, comprises about 25% of the coconut's total weight. It is widely consumed as a refreshing and nutritious beverage, low in calories, fat-free, and rich in minerals and electrolytes. As a versatile raw material, it is also used to develop various value-added products, including nata de coco, coconut jelly, nectars, wine, vinegar, fruit-based beverages, and lemonade.[5,6] The coconut kernel or coconut meat is the white part eaten as fresh or dried (as copra) and is processed into desiccated coconut, milk, cream, oil, flour, chips, strips, and flakes, each with distinct applications and benefits.[7] These products serve as base ingredients in fast-moving consumer products such as bakery items, ice cream, chocolates, and more. Beyond food, the kernel also supports the cosmetic, pharmaceutical, and animal feed industries. Coconut husk (47–50%) and coconut shell (14–15%) are primary by-products or waste and serve as raw materials for the coir-based, handicraft, textile, and construction industries. Furthermore, coconut husk, shell, and wood support renewable energy and sustainable farming through second-generation biofuels, biochar, briquetting, and composting applications.[8,9] Coconut serves as a food crop, oilseed, fibre crop, beverage crop, and a valuable raw material for multiple industries. Therefore, it has strong prospects for future growth and the ability to generate carbon credits, as it is a natural and environmentally favourable product.

The coconut sector is still growing steadily and has been contributing significantly to rural and economic development, but it is also plagued by a number of issues that prevent the full utilisation of coconut resources. In order to make the value chain feasible and have a greater long-term impact, technological and policy interventions are needed. In keeping with the goals of the 2030 Sustainable Development Agenda, this review establishes a perspective on the current state of coconut processing, identifies the major technological obstacles, and proposes sustainable solutions to address the operational and environmental problems.

2. The advancing field of coconut processing and value addition

The coconut is a valuable source of high-demand, value-added food and nutraceutical products due to its rich macro and micronutrient composition. The haustorium, inflorescence, kernel, and water are among the portions of the coconut that are used in processing since they have therapeutic benefits and are gaining global interest, which highlights opportunities in developing more value-added products.[10] These products are widely used in cuisine and are recognised for their nutritional value, antioxidant properties, and low glycemic index, making them appealing to modern health-conscious consumers.[11] Traditionally, coconut is processed into copra and oil. Still, due to demand, innovation and diversification have led to the emergence of a wide array of value-added products, including coconut vinegar, nata de coco, virgin coconut oil (VCO), coconut chips, coconut milk, snowball tender nuts, neera, coconut sugar, and more. However, more recently, there has been a shift toward producing more lucrative products, including those with high nutritional value and medicinal uses. For instance, coconut-derived medium-chain triglycerides (MCTs) and related medium-chain fatty acid (MCFA) derivatives have been associated with multiple health benefits and have gained prominent research and commercial interest.[12,13] As a result, coconut oil is being incorporated into innovative food products such as MCT-infused coffee, oil powder, oil-based mayonnaise, oleogel, and energy gels. Additionally, coconut kernel-derived products such as coconut milk, coconut cream, coconut yoghurt, cheese, and kefir offer various health benefits and culinary versatility due to their nutrient-rich composition and unique sensory profiles. Therefore, such innovative products fall under the current demand for clean-label, plant-based, and performance-enhancing foods.[14] Nowadays, innovative approaches are gaining momentum, such as nano-encapsulation that allows the incorporation of coconut-derived bioactives into functional foods, nutraceuticals, and cosmetics, intending to improve the stability and targeted delivery.[15] Furthermore, probiotic coconut milk beverages such as coconut kefir and coconut yoghurt are being developed with biotechnological approaches like fermentation with the help of the selected probiotic starter cultures.[16–18] For vegan and lactose-intolerant populations, coconut milk and cream are a significant source of plant-based lipid that helps in improving the texture, mouthfeel, and nutritional quality of plant-based food products. They are good substitutes for dairy fats due to their sensory and functional characteristics.[19] Such products made from coconuts offer the coconut industry significant agronomic and commercial prospects due to the growing demand for sustainable nutrition and vegetarianism worldwide.

To support these endeavours, there have been major advancements in process technologies as well. Various conventional thermal processing technologies, such as drying, fermentation, pasteurisation, and sterilisation, with or without the addition of chemical preservatives, are commonly used in coconut processing. These methods influence the shelf life, quality, and sensory properties of the final product, such as VCO, coconut milk, *etc.* The commercial processing of coconut products predominantly relies on conventional methods, owing to their practical simplicity and economic viability.[4] Various studies reported that these conventional technologies could not completely succeed in extending the shelf-life of such products resulting in unfavourable quality sensory changes.[20,21] To address these limitations several emerging thermal and nonthermal processing techniques, including microwave and ohmic heating, membrane filtration, ultraviolet treatments, ozonisation, cold plasma technology, supercritical carbon dioxide, high-pressure processing and microfluidization, are being investigated for their potential to improve the safety, stability, and overall quality of coconut-based products like tender coconut water, coconut milk, coconut cream, VCO, *etc.*[22–24] For instance, high-pressure processing has shown great promise in preserving tender coconut water as well as coconut milk-based beverages like coconut–cashew nut milk beverage by retaining more nutrients and flavour while extending the shelf life.[21,25,26] Similarly, advanced extraction techniques, such as ultrasound-assisted and enzyme-assisted extraction, enhance the yield and efficiency of VCO and bioactive compounds, reducing processing time and solvent usage.[27,28] Such concepts are driving the coconut industry beyond traditional applications, enhancing product diversity, quality, and market value, particularly in export-driven and health-conscious markets.

3. Current challenges in the coconut processing sector

The coconut industry is experiencing significant growth, though it faces numerous obstacles that hinder its expansion and sustainability. These challenges are multifaceted, including inconsistent raw material supply, market variations, labour unavailability, climate change, mechanisation, *etc.* Consequently, manufacturers, suppliers, and exporters need to overcome this variety of challenges. The main challenges are outlined below; in essence, these problems need to be resolved to guarantee the sector's long-term stability and growth in the future.

3.1. Raw material and availability

The availability of coconuts is frequently unpredictable due to pest and disease attacks, intensifying temperatures, unpredictable rainfall patterns, the increased frequency of cyclones, soil degradation, fragmented and monoculture farming practices, and water scarcity. These factors collectively lead to fluctuations in production, supply shortages, and rising prices.[29] Furthermore, over 80% of vulnerable coconut trees are destroyed by illnesses and attacks by major pests such as the rhinoceros beetle, red palm weevil, coconut mite, and coconut black-headed caterpillar. For instance, these pests are said to have decreased fruit productivity by 12–20% in West Africa, Brazil, Mexico, the Philippines, and Indonesia.[30] This also results in the production of small-sized and lower-quality coconuts, which have both direct and indirect financial impacts on the coconut sector. The relatively low rate of new plantations combined with an increasing number of senile coconut trees is another growing concern. The quality of fresh coconuts plays a crucial role in value addition; therefore, obtaining high-quality raw material is essential. Additionally, the quality of coconuts largely depends on factors such as variety, geographical conditions, cultivation and irrigation practices, and overall farm management.

3.2. Technical/scientific challenges

The coconut industry continuously faces technical and scientific challenges, including reliance on traditional agricultural practices, limited availability of high-yielding varieties (HYVs), inadequate pest and disease management (*e.g.*, whitefly and wilt), lack of technical awareness regarding harvesting and value addition, and insufficient research and development (R&D) support, which may limit the long-term sustainability of the coconut sector.[31] Collectively, these issues indirectly affect food safety, product quality, sustainability, production efficiency, and overall consumer satisfaction. For instance, many small and medium-scale oil processing units struggle with quality and safety management, often resulting in high free fatty acid levels, aflatoxin contamination, and improper packaging. These problems mainly arise from gaps in the scientific and technological understanding of quality control practices.[32] With respect to technological developments in the food industry, several green processing technologies, such as high-pressure processing, pulsed electric fields, and membrane processing, are currently being explored to improve the food safety and shelf life of coconut water, coconut milk, VCO, coconut cream, and other coconut-based products. However, adoption of these technologies is still limited by high investment costs, scale-up challenges, and regulatory barriers.[21,26]

3.3. Manpower and human resources

Farm mechanisation in many coconut-producing countries, across cultivation, harvesting, processing, and value addition, remains limited, resulting in a heavy reliance on manual labour. This leads to lower productivity, reduced efficiency, and diminished profitability, contributing to supply constraints and rising raw material costs. At the same time, changing aspirations among younger generations have led to a noticeable shift away from agriculture, with many preferring jobs in other sectors. A survey conducted in 2015 reported that workers in the coconut industry are increasingly shifting to alternative agricultural occupations that offer higher wages and better amenities, such as provided meals, making it harder for the industry to retain a stable workforce.[33] As a result, nowadays the coconut industry is continuously facing a leading labour shortage problem. Even if labour is available, there is often a lack of training and expertise in recent farming techniques, processing methods, and market orientation, which restricts the industry's ability to innovate and improve efficiency.[34]

3.4. Shrinking support resources

Extension and financial services provided to key stakeholders are essential for enhancing the long-term sustainability of the coconut sector. However, several studies reported that coconut growers and processors are experiencing a lack of support resources, including limited access to finance, reduced government assistance, insufficient training and extension services, inadequate research support, and poor access to market information. These constraints directly affect their ability to invest in improved processing practices and to respond effectively to market demands.[1,34] Consequently, many entrepreneurs continue to rely on outdated machinery, as modern equipment is often prohibitively expensive and beyond their financial capacity.[33] In addition, access to loans from financial institutions remains limited due to insufficient collateral. Addressing these challenges requires greater government involvement and stronger public–private partnerships to develop robust support networks for farmers, including education and training opportunities, marketing infrastructure, and improved access to essential inputs.

3.5. Infrastructure and investments

Inadequate infrastructure, including unreliable power supply, limited access to clean water, poorly developed road networks, insufficient storage facilities, and inadequate processing set-up, poses a major challenge to the growth and success of the coconut sector.[35] One classic example is the unit operation deshelling, reporting up to four accidents per month, mainly in workers following traditional practices, underscoring the urgent need for modernisation and the priority for workers' safety and industrial ethics. Therefore, investment in worker-friendly and efficient infrastructure and processing facilities is essential not only to protect labourers but also to ensure product quality and food safety.[36] Additionally, since coconuts are predominantly sourced from smallholders, the establishment of fully mechanised and well-equipped common processing facilities is essential to enable them to adopt modern technologies and advanced processing approaches.

3.6. Marketing and branding

Both traditional and emerging brands in the coconut sector struggle with inadequate marketing and branding, limiting their competitiveness in domestic and global markets. Even established brands struggle against modern competitors due to insufficient adaptation to new media marketing and branding strategies.[37] Moreover, agricultural commodities such as tea, coffee, and spices have established strong brand identities in global markets through Geographical Indication (GI) tags. In contrast, many coconut products lack a distinct brand identity, making it difficult to command premium prices in international trade. Furthermore, challenges such as forced sales, excessive market charges, unethical trading practices, a high number of intermediaries, low consumer awareness, poor packaging, inefficient supply chain management, and the absence of co-branding or digital marketing strategies further suppress demand for value-added coconut products, including VCO, coconut-based beverages, and functional health foods, ultimately weakening brand visibility and consumer trust.[38,39]

3.7. Export/import barriers and regulations

Export barriers and trade regulations, particularly those related to allergen labelling, pose significant challenges to the coconut industry and limit market access, thereby indirectly reducing the export potential of coconut products, especially in markets such as the United States and the European Union. Coconut food product exporters faced several challenges due to coconut being classified as a tree nut under the Food Allergen Labelling and Consumer Protection Act of 2004 (FALCPA). This misclassification had resulted in confusion among consumers with tree nut allergies and prevented them from consuming coconut products. Exporters had to comply with such allergen labelling requirements, but now that coconut is categorised as a fruit, these regulations have changed.[40] In addition, coconut oil is often viewed by the public as potentially harmful to health. According to the International Coconut Community (ICC), many of these concerns are based on incomplete or misinterpreted information rather than strong scientific evidence. As a result, negative perceptions about coconut oil are largely driven by public belief rather than proven health risks. Also, obtaining an import–export certificate from the Directorate General of Foreign Trade (DGFT), which is mandatory for export activities, is often costly and involves extensive documentation, posing significant challenges for small- and medium-scale coconut industries. In addition, the growing incidence of food fraud, adulteration, contamination, health-related concerns, natural disasters, and geopolitical tensions has further compounded these challenges. Particularly, the coconut export sector has now been increasingly affected by such disruptions, leading to higher logistics costs. Collectively, these factors hinder the industry's ability to grow and remain competitive, especially in global markets.

3.8. Waste utilisation/management and practices

The coconut industry generates a considerable volume of waste/byproducts, including coconut husks, shells, coconut water, and testa. Coconut husks are abundant agricultural by-products, with over 50 million tons generated annually from the global coconut processing industry.[41] Approximately 62–65% of the whole coconut fruit goes as waste in the form of husks and shells, which are often burned or dumped, causing heavy pollution concerns.[42] Countries like India and Sri Lanka have successfully utilised these by-products and are currently the main producers and exporters of husk- or coir-based products. However, even in India, coir production remains limited; according to the FAO, global coir production in 2019 was estimated at 1.26 million tonnes, with India accounting for nearly half (518000 tonnes).[43] This indicates that bulky quantities of coir remain unutilized. Additionally, a significant amount of coconut water is directly dumped into soil or water bodies, contributing to soil and water pollution.[44] When it comes to green coconut shells, every tender coconut consumed produces approximately 1.53 to 2.64 kg of shell waste (husk + shell), depending on whether it is a local or hybrid variety.[42] Green coconut shells can take up to ten years to decompose in the environment, making urban areas unsightly and serving as breeding grounds for mosquitoes and disease-transmission vectors.[45] The disposal of green coconut shells is frequently unregulated and usually takes place in unsuitable locations like beaches and abandoned lots. Underutilization of these waste materials presents a major challenge, leading to both environmental and economic losses. As a result, the coconut processing industry, currently, may not be operating sustainably, primarily due to the absence of a circular economy approach. Implementing a circular economy is crucial, and it is imperative to clearly understand the distinctions between 'product', 'by-product', and 'waste' in the context of this highly versatile commodity.

4. Sustainability strategies for the coconut processing industry

The development and growth of the coconut industry have been constrained by multiple uncertainties, including inefficient resource use, inadequate waste management practices, fragmented supply chains, and increasing environmental impacts. These challenges continue to limit the sector's ability to achieve large-scale agro-industrial transformation. Addressing these issues is therefore essential to ensure the long-term sustainability and optimal performance of the industry, in alignment with the United Nations 2030 Agenda for Sustainable Development Goals (SDGs).

A SWOT analysis of the coconut processing sector, presented in Table 1, highlights strong potential in terms of product diversification and growing global demand, while also identifying key weaknesses such as poor waste utilisation and limited access to modern technologies. Opportunities lie in circular economy innovations and the development of value-added products, whereas threats include market volatility, labour shortages, and the impacts of climate change. Understanding these factors is critical for designing effective sustainability strategies that respond to the evolving needs of the industry. Accordingly, this section outlines various sustainability strategies that can be adopted by coconut processing industries to reduce environmental impacts while creating economic value, thereby contributing to the achievement of the SDGs. Each strategy suggested below is supported by relevant examples drawn from within and beyond the coconut processing sector.

4.1. Use of natural additives and ingredients

The use of natural ingredients, combined with waste-to-wealth approaches, strengthens the sustainability and resilience of the coconut industry by supporting clean-label initiatives and reducing reliance on synthetic additives. At the same time, it encourages innovation in processing technologies by blending modern techniques with time-honoured traditional practices, thereby improving environmental performance, resource efficiency, and overall product quality. For instance, incorporating natural ingredients, particularly herbal plant extracts for VCO and smoke for copra, to extend shelf life is gaining attention as a value-added or traditional processing approach rather than as the use of additives. The degradation of unsaturated fatty acids in edible oils leads to a marked decline in oil quality, affecting flavour, storage stability, and nutritional value. Therefore, to slow down the lipid oxidation, most oil-processing industries rely on synthetic antioxidants such as butylated hydroxyanisole (BHA), butylated hydroxytoluene (BHT), and tertiary butylhydroquinone (TBHQ), typically at concentrations of up to 200 ppm. However, several studies have shown that the incorporation of natural antioxidants derived from herbs and spices, including ginger, cinnamon, beetroot, garlic, nutmeg, pepper, cloves, and strawberry into VCO can further improve the oxidative stability and resistance to spoilage.[46,47] A notable example is the tribal communities in the Andaman and Nicobar Islands, who produce VCO enriched with local herbal extracts to enhance the oil's purity, healing properties, and shelf life. According to Intellectual Property India, this traditional method, which has earned a GI tag, showcases the value of indigenous knowledge in developing eco-friendly and culturally rooted coconut products.[48]

In many coconut-growing countries like India, Sri Lanka, the Philippines, and Indonesia, copra is one of the major traditional products processed from coconuts by small landholder farmers as a key ingredient to produce coconut oil. Traditionally, farmers generally process copra by smoking, in which the coconut cups are spread on the platform in an open space, and coconut husk is burnt underneath, and the smoke and burnt gases directly contact the drying coconut cups.[49] However, this method also leads to air pollution due to the release of smoke and particulate matter. As a sustainable alternative, liquid smoke is gaining attention in the food industry as a clean-label component due to its natural origin and versatility. It is produced through the pyrolysis of wood, which contains acetic acid and phenolics, naturally occurring antioxidants and antimicrobials. These properties make it an effective natural preservative, aligning with consumer demand for minimally processed and additive-free foods. Grade 2 liquid smoke is deemed safe for human consumption when used as a preservative. Numerous studies have demonstrated the effectiveness of coconut shell-derived liquid smoke in extending the shelf life of various food products, including mackerel scad fish[50,51] and tofu.[52] Its use as a natural preservative in edible coatings developed from chitosan has been found to increase the shelf life of foods such as barracuda fish sausage and chikuwa.[53] Furthermore, utilising liquid smoke to preserve meat could eliminate the need for chemical cleaners in traditional smokehouses, thereby reducing cleaning costs and sewage management expenses. Budy Rahmat *et al.*[54] reported that in the processing of coconut meat, white copra treated with 12.5% liquid smoke achieved quality equivalent to that of sulfur fumigation, being free from fungal infection and showing the highest oil yield and copra brightness. However, more scientific research and pilot-scale studies are needed to optimise liquid smoke production, standardise its application methods for copra drying, and assess its effectiveness on a commercial scale. Adopting these environmentally beneficial, traditional knowledge-based solutions contributes to the preservation of cultural heritage, strengthens local communities, and advances coconut processing toward a more sustainable future.

Table 1 SWOT analysis on the coconut processing industry

Strengths (internal positive factors)	Weaknesses (internal negative factors)
1. Versatility of the product 2. Sustainable source of 5 Fs, *i.e.*, food, feed, fuel, fibre, and fertilisers 3. Livelihood support to millions of farmers in the tropical region 4. Supports biodiversity and the highest land use pattern 5. Established global market presence	1. Consisting mainly of small and medium-sized units 2. Unpredictable raw material supply and quality requirements 3. Lack of infrastructure and supply chain facilities 4. Insufficient mechanisation 5. Limited technological adoption due to high investment and lack of awareness 6. Issues in marketing and branding 7. Poor handling of generated wastes 8. Water and energy-intensive processing 9. Insufficient support and policies for the coconut industry

Opportunities (external positive factors)	Threats (external negative factors)
1. Rising demand in culinary, cosmetics, pharmaceuticals, and personal care	1. Vulnerability to climate change and natural disasters
2. Research and development opportunities for innovative coconut-based products	2. Raw material price fluctuations
3. Integration of circular economy principles for environmental improvement	3. Shortages of labour
4. Sustainable agro-industrial transformation of the coconut industry through life cycle assessment	4. Volatility in the global market
5. Policy & innovation support	5. Trade barriers and export restrictions
6. Social and ethical responsibility	
7. Digitalisation in the supply chain and transparency	
8. Water and energy security	

4.2. Reduced usage of chemicals and organic solvents

The practice of using fewer chemicals and organic solvents with the adoption and implementation of new and eco-friendly processing technologies, such as high-pressure processing, ultrasonication, pulsed electric field processing, supercritical CO_2 extraction, enzymatic hydrolysis, and membrane filtration, would be an important and promising area for the coconut sector. The use of such technologies in the coconut sector reduces chemical usage, enhances extraction efficiency and product safety, and helps in preserving the nutritional and sensory quality of coconut products. However, their widespread adoption is limited by high capital costs, technical complexity, and scalability challenges, particularly for small and medium coconut processing units. Overall, this approach enhances product quality, ensures environmental safety, supports regulatory compliance, and unlocks new market opportunities.[21,55] For instance, the valorisation of coconut water into a high-value powder through spray drying without artificial preservatives and the preservation of coconut water using high-pressure processing techniques have been reported to maintain quality and partially reduce microbial growth, thereby extending shelf life. Nevertheless, chilled storage remains necessary to ensure safety.[26,56] Leena *et al.*[57] reported that nanomembrane filtration is an innovative, chemical-free approach for extending the shelf-life of neera (inflorescence sap) without the use of high temperatures, as employed in most conventional processes, thereby minimising quality changes. Such approaches can serve as alternatives to conventional techniques that need to be adopted in the coconut industry.

Similarly, the purification/refining of coconut oil is carried out through chemical processes, which involve the use of chemicals to remove impurities and obtain clear, refined oil. Membrane technologies can be used to achieve degumming, deacidification, bleaching, dewaxing, catalyst recovery, and other steps in oil refining processing, thereby eliminating the need for chemical use. Membrane filtration can result in up to 65% energy savings in terms of solvent evaporation and can replace up to 50% of conventional deacidification and bleaching processes.[58,59] However, the approach may be costly and require regular maintenance of the membranes. Therefore, Rangaswamy *et al.*[59] suggested that pilot demonstration plants should be established and operated for 1–2 years to understand and overcome the practical challenges and limitations of the technology, paving the way for its industrial adoption. Several studies have reported that refining oil using activated charcoal or zeolite filtration significantly reduces free fatty acid (FFA) and moisture content, thereby minimising the need for chemical use. In the refining process of coconut oil, activated charcoal is used at a concentration of 1.5%, achieving a clarity level of 97.83% transmittance (T), a moisture content of 0.016%, and a FFA level of 0.006%.[60] Overall, such nonthermal processing techniques align with sustainable development by reducing chemical effluents and supporting clean-label products. Although they are advantageous, the commercialisation of these revolutionary technologies is currently being improved and worked on in terms of initial investments and the possible requirement of a cold chain after processing, up to utilisation. Adoption of these eco-friendly, energy-efficient technologies might boost export potential, encourage industrial innovation, and satisfy growing consumer demand for natural, minimally processed coconut-based beverages and/or other products.

4.3. Effective usage of resources

Resource efficiency in the coconut industry is crucial for achieving sustainable transformation and maintaining competitiveness in a resource-constrained environment. This includes reducing waste across the product life cycle, lowering energy and water consumption, sourcing recyclable inputs, and applying circular economy principles. The strategy contributes directly to the sustainability of the planet and financial viability. In addition, ensuring food availability, jobs, and natural resources conservation is considered. For instance, the husk can be converted into coir fibre or fertiliser, the shell into either activated carbon, crafts, or liquid smoke, the flesh into flour, and the coconut water into beverages or fermented products. Such activities generate job opportunities for nearby communities, thereby contributing to livelihood support at the local level.[61–63] This strategy of using the coconut entirely ensures that negligible to no part of the coconut goes to waste, which is in line with the principles of the circular economy.[8]

Processing operations like dehusking, oil and milk extraction, heating and cooling, and value-added product production, including production of activated carbon and liquid smoke, require large amounts of water and energy. Fig. 1 represents the relative water requirements to produce different value-added food products from coconuts. To achieve better sustainability, there is an imperative need to optimise resource utilisation *via* green energy strategies. This includes drying of coconut meat using solar dryers for copra production and energy generation with biomass from coconut husks for drying and boiling. Therefore, the adoption of renewable energy resources and efficient processing equipment can significantly improve resource utilisation and reduce environmental impacts as well. For instance, mechanised desiccated coconut (MDC) processing units play an important role in lowering the overall water footprint of production.[64] In addition, the use of biomass-powered dryers has been reported to reduce drying time by up to 62.5% while requiring less fuel, with consumption rates of only 0.5–0.75 kg per hour.[65]

Resource-use efficiency in the coconut industry is strongly influenced by the choice of processing techniques, as these determine both product yield and the effective utilisation of raw materials. For instance, the adoption of non-thermal process intensification technologies, particularly ultrasonication and pulsed electric fields, enables the efficient extraction of high-quality VCO while maximising raw material and energy use and reducing processing time. These approaches not only enhance product yield and preserve nutritional quality but also align with the principles of resource-efficient and sustainable food processing.[20] Additionally, replacing synthetic pesticides and fertilisers with biochar and green coconut shell liquid, respectively, contributes to improved soil health and biodiversity. Furthermore, shifting towards biodegradable packaging and using natural additives not only enhances clean-label products promotion but also reduces environmental impact.[66] By minimising waste, maximising value, and conserving natural resources, the industry can contribute to a more sustainable, resilient, and equitable food system for current and future generations.

4.4. Energy-efficient processes

Food manufacturing processes, such as processing, packaging, transport, and post-production stages, are the main sources of greenhouse gas emissions in the food industry, mainly due to their high energy consumption. Together, the food manufacturing and post-production stages account for about 70% of total energy consumption within the system.[67] Coconut processing into value-added products like coconut cream, coconut sugar, VCO, desiccated coconut, activated carbon, and coir is energy-intensive, and a summary of selected products is presented in Table 2; high energy requirements can significantly contribute to greenhouse gas emissions.[65,68] Integrating energy-optimisation strategies, such as optimising process parameters, modifying equipment design, adjusting production schedules, staggering operations, enhancing equipment

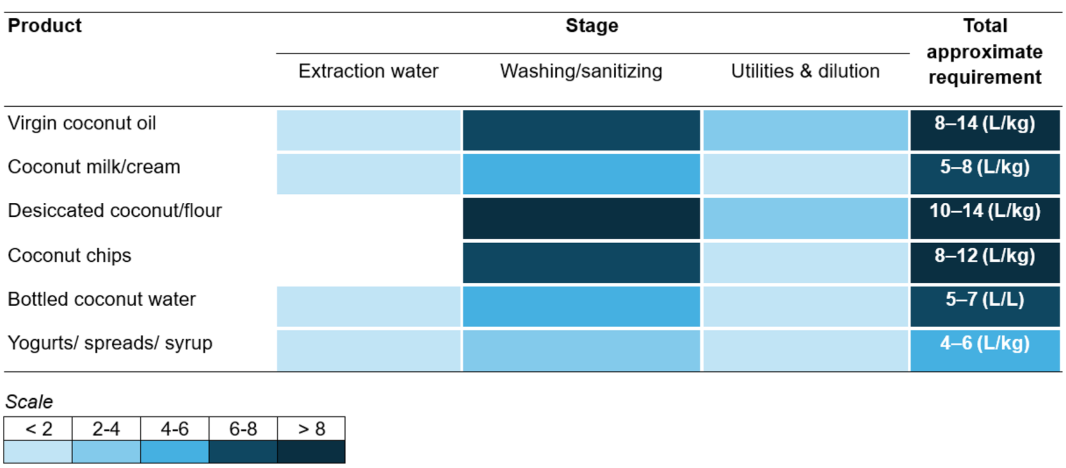

Fig. 1 Relative water requirements to produce different value-added food products from coconuts.

controls, and adopting continuous processing, can reduce energy consumption, lower environmental impact, and boost economic viability.[67,69] For example, the use of hybrid solar-biomass or waste heat-assisted dryers can decrease fossil fuel reliance during the energy-intensive drying stage of copra and oil production. These types of drying systems make effective use of biomass residues, such as coconut shells and husks, thereby supporting circular resource utilisation.[65] Similarly, the recovery of waste heat through the installation of heat exchangers and thermal energy storage systems can result in significant energy savings within the food industry. In addition, the integration of renewable energy sources, including solar photovoltaics and biomass gasification, further enhances sustainability in coconut processing facilities. For instance, a Cargill plant in Songyuan City, China, utilises a fuel blend containing 5–6% rice husk mixed with coal, which has helped reduce coal consumption and lower emissions by approximately 17 600 metric tonnes.[70] Also, by implementing continuous drying technologies instead of batch drying, the desiccated coconut industry can enhance productivity, improve energy efficiency, and align more closely with SDGs. Therefore, optimising energy use and adopting renewable sources in the coconut industry fosters cleaner production and supports a circular, low-carbon industry.

4.5. Plant sanitation and safety

Clean-in-Place (CIP) is a thermal cleaning process commonly used in the food industry, which uses non-biodegradable chemicals such as acids and alkalis to sanitise production equipment, tanks, and pipelines within a closed-loop system. With limited reports on the coconut processing industry, an example of the dairy sector is presented here: In Germany, 2000 and 6000 tonnes of these chemical agents are used annually from the dairy industry and must be neutralised before being discharged into effluent streams. Moreover, CIP is energy- and water-intensive, posing significant environmental concerns. For instance, for cheese manufacturing, CIP is the third highest energy consumer and uses around 10% to 29.5% of the total water.[71,72] Installing enzyme-based CIP systems is emerging as an innovative and eco-friendly alternative to conventional chemical cleaning systems used in the food and agro-processing industries. These systems are currently in the research and development stage, but preliminary studies have reported several sustainability benefits. These include lower operating temperatures, which result in energy savings, shorter cleaning cycles, reduced wastewater treatment costs, and less water usage due to less rinsing. Enzymes, being naturally based, are biodegradable, easy to inactivate, and non-toxic and do not produce harmful by-products. As such, enzymes are a more environmentally friendly alternative to conventional chemical agents.[71,73] Additionally, smart CIP systems and enzymatic biosensors are different technologies that improve sustainable sanitation by decreasing resource consumption and allowing for instant contaminant detection.[72,74] These developments enhance overall process efficiency and promote cleaner production.

Although enzymatic CIP and enzymatic biosensors have demonstrated good performance under controlled conditions, their large-scale industrial commercialisation remains limited due to high costs associated with enzyme use, expertise dependence, unstandardized processes, and, notably, a lack of awareness within the dairy and beverage industry. Consequently, it would be imperative that scientists working on CIP systems focus on optimising enzyme composition and cost-effectiveness as a strategy for large-scale adoption within industries such as coconut processing, which requires emphasis on hygiene and environmental considerations. CIP enzymatic systems, encouraged by the food and coconut industries, and promoting environmental conservation and shifts toward greener and cleaner sanitation practices, bring a greener and more sustainable perspective within the scope of the coconut processing industry.

4.6. Waste and by-product utilisation

The coconut industry generates a lot of waste at different levels of processing, including husk, shell, water, testa, *etc.* If this waste is not managed properly, it can lead to environmental damage and inefficient use of resources. Many coconut industries operate on a linear economy and do not pursue value addition, perhaps due to a lack of knowledge and technological gaps, coupled with limited awareness. For instance, an average of 3200 million litres of coconut water per year is released into the environment without adequate treatment by the Indian copra industry alone.[44] Several researchers have pointed out that the adoption of circular economy approaches, such as the development of value-added products, marketable fast-moving

Table 2 Energy-intensive unit operations involved in the production of value-added products from coconuts

Product	Primary energy uses
Virgin coconut oil (VCO)	Grating, fermentation (or heating), centrifugation, filtration
Coconut milk/cream	Grating, hot water extraction, filtration, homogenization, pasteurization
Desiccated coconut	Blanching, drying (hot air), milling
Coconut chips	Slicing, blanching, drying (vacuum or hot air), frying (optional)
Coconut flour	Milling of residue, drying, sieving
Coconut water (bottled)	Sterilization, chilling, bottling, labelling
Coconut vinegar	Fermentation control (aeration, temp), bottling
Coconut sugar (from neera)	Boiling of neera sap, drying, sieving
Coconut yoghurt/spread/jam	Blending, heating, pasteurization, cooling

consumer goods, biofuels, organic fertiliser, eco-friendly technologies, and strategic alliances, aligns with international trends to ensure a sustainable and equitable agro-industrial future of the coconut sector.[8,75]

Therefore, through creative methods, coconut waste, commonly viewed as garbage, can be converted into valuable products, which innovatively promote sustainability and contribute to economic development. Fig. 2 presents details of the various types of waste generated during desiccated coconut processing from a circular economy perspective. The major wastes generated from desiccated coconut industries include husk, shell, coconut water, and testa. Among these wastes, coconut water and testa are largely overlooked despite having strong potential for generating additional value-added streams. For the sustainability of the coconut industry, turning these byproducts into beneficial secondary products is a substantial opportunity. With a circular economy perspective, it will be possible for industries to reduce waste generation and sustain more lucrative streams with less carbon footprint. By promoting waste-to-value generation, it will not only be an area for sustainability but will, in fact, sustain and develop an economically stable scenario with regard to the coconut processing sector. Moreover, it will contribute positively towards enhancing the socio-economic status of people associated with desiccated coconuts, thereby contributing to the achievement of the SDGs (Fig. 3). Therefore, coconut waste becomes a powerful resource for driving environmental sustainability, social inclusion, and economic development in alignment with the 2030 agenda for Sustainable Development (UN) and SDGs (Table 3).[76–90]

Furthermore, another sustainable way to manage coconut waste directly is by setting up small-scale decentralised facilities for the processing of coconut waste, near to or at the site of coconut production. These facilities serve as miniature value-adding centres by converting waste into products that may be used or sold. Additionally, they support local value creation, assist rural entrepreneurship, lower transportation costs, and encourage environmentally beneficial behaviours through recycling and resource recovery.[91] There is, however, a need for future research and policy support for developing accessible, user-friendly technologies and focused training to be imparted to local communities to ensure the decentralised units of coconut waste processing would be viable. On the other hand, the development of eco-friendly branding and market linkages that support demand for value-added products will generate long-term economic and environmental benefits.

4.7. Reduced carbon footprint

An essential strategy for the sustainability of the coconut processing sector would be lowering carbon emissions throughout the product lifecycle, processing methods, and supply chain. The implementation of this scientifically grounded strategy necessitates a multi-tiered, evidence-based approach to support climate action and enhance operational sustainability, including improvements in resource use efficiency, waste valorisation, sustainable transport logistics, clean energy adoption and ecosystem restoration. The coconut industry must transition toward renewable sources such as solar and biomass-based energy derived from coconut residues through briquettes, biochar, second-generation fuels, biogas, and fertiliser, thereby

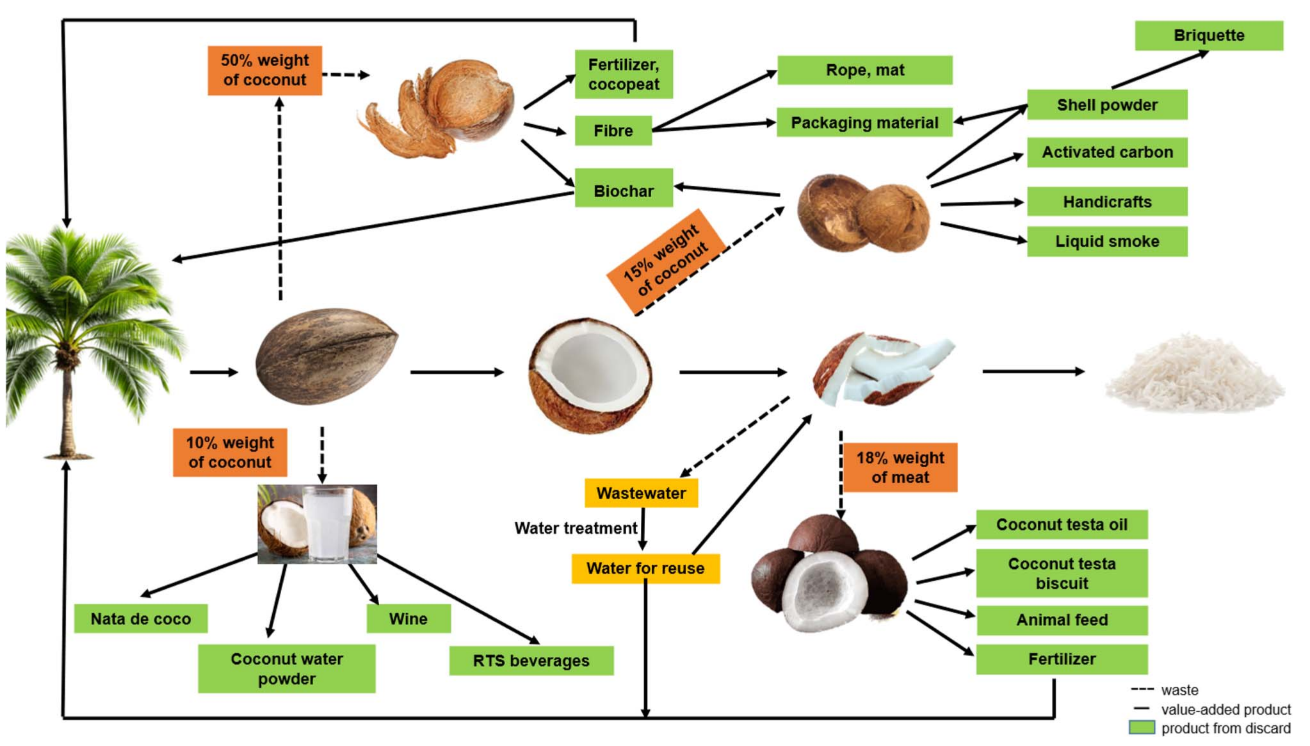

Fig. 2 An example of effective waste management considering a circular economy approach for the desiccated coconut industry.

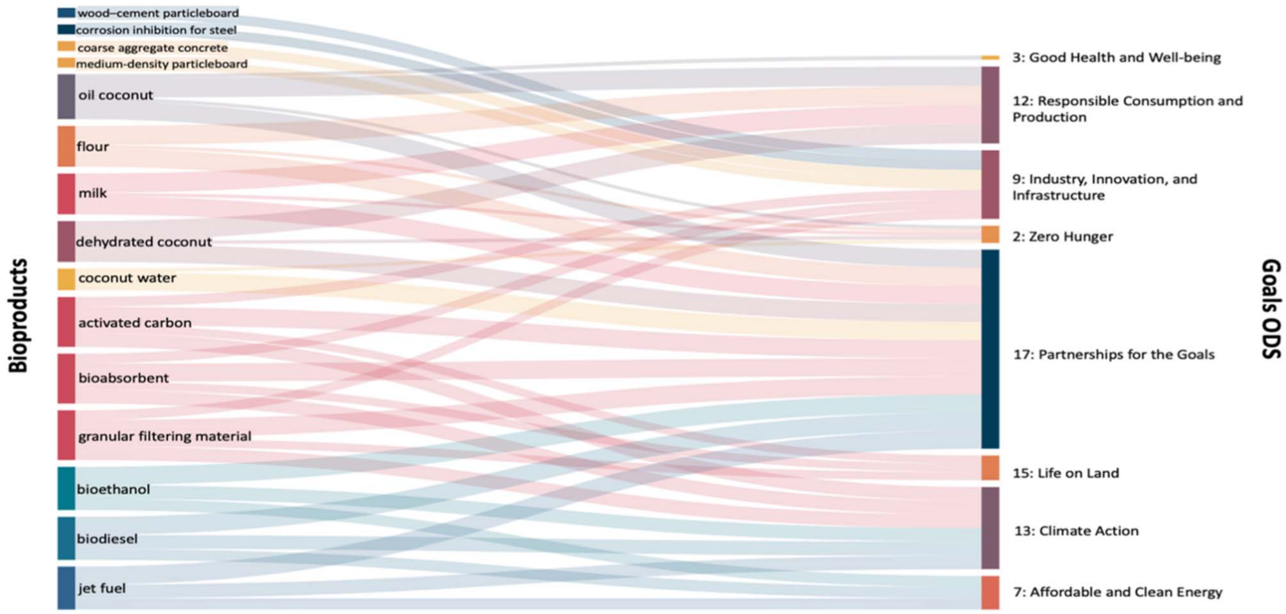

Fig. 3 Coconut products as catalysts for Sustainable Development Goals (SDGs) 2030 reproduced from ref. 8 with permission from [MDPI], [F. Vieira, H. E. P. Santana, M. Jesus, J. Santos, P. Pires, M. Vaz-Velho, D. P. Silva and D. S. Ruzene, *Sustainability*, 2024, **16**(7)], copyright 2024.

reducing greenhouse gas emissions and enhancing energy security.[66,92,93] For instance, about 12 000 tons of coconut charcoal briquettes are produced yearly by Tom Cococha, an Indonesian firm that provides a sustainable substitute for fossil fuels and wood-based energy sources. The company greatly lowers CO_2 emissions and promotes waste valorisation in the coconut sector by producing briquettes from coconut shells, an agricultural by-product. This is an example of the circular economy concept in action, as well as a way to mitigate climate change.[94]

Similarly, many studies are available on the production of briquettes from dry coconut husk, which is well-suited for industrial applications. The processing of 946 250 kg of green coconut shells into briquettes reduces greenhouse gas emissions by approximately 40 000 tons per year, while landfilling around 5000 m^3 of leachate is produced annually as a pollutant harmful to both the environment and human health.[9,84] Sourcing raw materials locally within 50 km of a processing facility might significantly reduce transportation costs and carbon emissions. An interesting finding reported that farm-level application of biochar can offset between 727 000 and 882 000 metric tons of CO_2-equivalent emissions through a reduction in fertiliser use.[95] Additionally, coconut biochar has a wide range of applications, including use as a soil conditioner to enhance crop yields, reduce fertiliser costs, improve soil pH and physical properties, alter soil microbial populations and functions, and minimise environmental impacts on soil and water.[9,66] The use of tender coconut husk in the form of biochar could enhance soil fertility, reduce dependence on chemical inputs, and boost overall farm productivity. Hence, promoting the use of tender coconut husk briquettes and biochar supports the coconut industry by transforming waste into valuable products. This approach helps to build a more sustainable sector while fostering innovation for a healthy circular economy that benefits both livelihoods and the environment. Overall, to make this a reality, empowering stakeholders and promoting innovation through policy incentives, targeted training, and research support are crucial.

4.8. Sustainable packaging solutions

In the food sector, packaging is critical for extending shelf life, decreasing food waste, and promoting the product. Principally, 50% of food packaging material is utilised as single-use plastic produced from petroleum-based plastic polymers, and the chances of recycling are extremely low. Traditional packaging has performed as a cost-effective and convenient solution. Still, it contributes significantly to land and marine pollution, landfill trash, resource depletion, damaging wildlife and the ecosystem, greenhouse gas emissions, and so on.[96,97] In contrast, sustainable packaging materials and processes prioritise renewable resources, waste reduction, and recyclability while leaving a smaller environmental footprint.

Nowadays, many sustainable and biodegradable packaging solutions are available, and most major players in the food industry are committed to reducing post-consumer plastic waste. To address this issue, companies are increasingly adopting biodegradable packaging materials. As part of its multi-dimensional initiative, ITC Limited has launched its Sustainability 2.0 vision and is working toward ensuring that 100% of its packaging is reusable, recyclable, or compostable/biodegradable. It has introduced biodegradable packaging solutions for its wheat flour brand, demonstrating its commitment to environmentally responsible practices.[98] If such packaging materials are used for coconut-based products, industries can significantly reduce plastic waste, enhance the eco-friendly

Table 3 Coconut waste utilization and its alignment with the SDGs

SDG	Relevant indicator(s)	Type of impact	Scope and relevance	References
1 NO POVERTY	1.1. People below the poverty line 1.5. People affected by disasters	Social/economic	• Creates rural employment and small-scale business opportunities through waste-based products • Income generation through value-added products from waste (*e.g.*, coir, biochar, *etc.*)	61 and 76
2 ZERO HUNGER	2.2. End all forms of malnutrition 2.4. Sustainable agriculture practices	Environmental/social/nutritional	• Incorporating coconut meal into items like fortified flour, protein bars, and porridge mixes can help to address undernutrition and micronutrient deficiencies • Coconut waste in the form of compost, biochar, and bio-fertilisers enhances soil fertility and crop yield	77 and 78
3 GOOD HEALTH AND WELL-BEING	3.9. Reduce illnesses from hazardous chemicals and air, water, and soil pollution and contamination	Social/health/environmental	• The use of coconut oil in personal care items such as hair oils, body moisturisers, soaps, and creams • Extracting useful bioactive compounds from coconut husk, shell oil, and coir-derived ingredients will help in the development of speciality products providing anti-inflammatory, antimicrobial, and skin barrier-enhancing activity without using synthetic chemicals and preservatives	79 and 80
6 CLEAN WATER AND SANITATION	6.3. Improve water quality by reducing pollution, eliminating dumping, and minimising the release of hazardous chemicals	Environmental	• Dye extracted from green coconut shells can be used in the textile industry as a natural alternative to artificial dyes, thereby decreasing pollution by chemicals • Because of the good adsorption properties of coconut shell charcoal and coir, they could be used in water filtration and pollution control	81–83
7 AFFORDABLE AND CLEAN ENERGY	7.2. Increase the share of renewable energy in the global energy mix	Environmental/economic	• Green coconut shells can also be converted into biochar or briquettes, which not only serve as a sustainable fuel source but also help to reduce carbon emissions • Production of bioethanol from green coconut husk fibres is considered a renewable source of energy	84–86
8 DECENT WORK AND ECONOMIC GROWTH	8.3. Promote development-oriented policies that support productive activities, decent job creation, entrepreneurship, and innovation	Economic/social	• Supports livelihoods in processing, coir industries, and value-added product sectors • Production of organic fertilisers opens employment opportunities in rural and semi-urban areas, particularly for women and small-scale entrepreneurs	61 and 84

Table 3 (*Contd.*)

SDG	Relevant indicator(s)	Type of impact	Scope and relevance	References
9 INDUSTRIE, INNOVATION UND INFRASTRUKTUR	9.4. Upgrade infrastructure and industries for sustainability and resource efficiency	Economic/ environmental	• Promotes green technology and innovation in sustainable product development, like composites, and biodegradable packaging • Use of coconut residues in civil construction, producing materials like particleboards and wood–cement particleboards	87 and 88
11 SUSTAINABLE CITIES AND COMMUNITIES	11.6. Reduce the environmental impact of cities, including waste management	Environmental/ social	• Reduces solid waste volume through recycling and reuse in both urban and rural areas • The development of local coir-based enterprises creates green jobs that support community livelihoods and contribute to a cleaner and safer environment for human life	76 and 89
12 RESPONSIBLE CONSUMPTION AND PRODUCTION	12.5. Substantially reduce waste generation through prevention, reduction, recycling, and reuse	Environmental/ economic	• Encourages circular economy practices and reduces resource depletion • Development of sustainable alternatives, such as coconut flour, milk, and desiccated coconut, contributing to responsible consumption practices	23,24 and 90
13 CLIMATE ACTION	13.2. Integrate climate change measures into national policies, strategies, and planning	Environmental/ economic	• By converting shells, husks, and coir into biochar, briquettes, compost, and organic fertilisers, the industry will reduce greenhouse gas emissions from open burning and synthetic fertiliser use	45 and84
15 LIFE ON LAND	15.3. Combat desertification, restore degraded land and soil, and strive to achieve a land degradation-neutral world	Environmental	• Organic mulch and compost improve the soil properties for sustainable land use • Use of coconut biochar for treating acidic soils, as well as promoting sustainable use of the land and ecological health	9 and 66
17 PARTNERSHIPS FOR THE GOALS	17.17. Encourage effective partnerships between public, public–private, and civil society	Social/ institutional/ global cooperation	• International trade of coconut products also plays a role in economic cooperation and worldwide business connections. Partnerships ensure information sharing, technology transfer, and capacity building, which will greatly benefit the small-scale growers and manufacturers	61 and 84

appeal of the products, and align the industry with global sustainability standards. This strategy not only enhances the market value of the product, but also meets the growing consumer demand for environmentally friendly packaging.

Additionally, one of the most important parts of the coconut is the husk, which is often considered waste, yet it has significant potential as a sustainable source of packaging materials due to its high polyphenol content, ease of processing, and wide availability. Several studies have reported that coconut husk can be successfully converted into a wide range of value-added products, including antimicrobial coatings, biodegradable paper, composites, and bioplastics.[87,99] Additionally, packaging materials derived from coconut fibres, such as boxes, trays, and wraps, also provide an earthy, natural aesthetic that aligns well with sustainability-focused brands and clean-label marketing strategies. Hence, the utilisation of husk as a packaging material addresses multiple sustainability dimensions. As a biodegradable material, husk-based packaging decomposes naturally without releasing harmful substances into soil or water systems and helps conserve soil structure and water quality. From an economic perspective, this approach adds value to materials that are traditionally considered as waste, thereby creating additional income opportunities for farmers and rural communities. Socially, the production of coconut-based packaging materials can generate employment, particularly in rural areas. Overall, adopting such approaches within the coconut industry can reduce waste, stimulate innovation, and support the development of rural economies.

4.9. Land use and environmental impact

Millions of farmers' livelihoods depend on the coconut industry; therefore, it is important to improve the standard of living of smallholder farmers through sustainable production while also protecting ecosystems. Hence, there is an urgent need for the coconut sector to adopt integrated land-use practices and sound environmental policies. Additionally, the demand for coconut and coconut-based products continues to rise, which will likely drive the expansion of land under cultivation. If this growth is not sustainably managed, it may lead to environmental challenges such as deforestation, biodiversity loss, soil degradation, water contamination, and increased greenhouse gas emissions. Agroforestry integrates trees, crops, and livestock within the same area, thereby providing a sustainable land-use system that can mitigate the environmental impacts and socio-economic challenges faced by the coconut industry.[100,101] This approach ensures raw material stability, reduces market risks, and limits monoculture-related vulnerabilities, as unavailability of raw material is the major problem faced by the coconut industry.

As reported by Dissanayaka *et al.*[102] and Dissanayaka *et al.*,[103] integrating agroforestry with coconut cultivation reduces crop failure risk, promotes diversified food production that contributes to household nutrition and surplus income, and enhances ecosystem functions. These benefits include improved biodiversity and soil quality, better control of pests and diseases, reduced dependence on chemical inputs, support for integrated coconut-livestock farming systems, enhanced carbon sequestration, and reduced greenhouse gas emissions. Jha *et al.*[104] reported that integration of integrated crop farming or land use change can reduce green house gas emissions up to 80%, a 63% reduction in agricultural water use, and self-sufficiency in agricultural products by 2050.[104] In addition, wastewater must be treated with effective effluent treatment plants to avoid water body contamination and ensure public health protection. Microalgae culture for wastewater treatment is an efficient way to minimise the environmental footprint on water bodies.[105] Moreover, it has the prospect of providing additional revenue to the industry from algae-based feed production. Today, most food processing industries are embracing such methods as part of their sustainability strategy. Microalgae farming, for example, has been adopted by the effluent treatment plant of a fruit processing facility in Sahyadri Farms, Nashik, India.[106] Therefore, embracing a sustainable land-use strategy ensures environmental well-being and economic stability, hence emerging as a practical approach towards sustaining the coconut sector in the face of climate as well as market uncertainty. Combined land-use and environmental policies are also in support of the above by promoting sustainable production, protecting ecosystems, and improving smallholder livelihoods.

5. Other key considerations

Since sustainability encompasses all aspects beyond environmental consideration, other determining factors need to be considered to guarantee long-term coconut industry sustainability. Staying limited to core environmental principles might lead to neglecting very important elements affecting the long-term viability and equity of the industry. These additional elements, such as labour safety and welfare and greater transparency, strengthen resilience across the entire value chain, promote growth, and help identify underlying risks. By considering these elements as an important strategy, the coconut sector can adopt a more holistic, balanced, and forward-looking sustainability approach that equally benefits people, the economy, and the environment.

5.1. Social and ethical responsibility

The long-term sustainability of the coconut industry demands the adoption of strategies that are deep-rooted in social and ethical responsibility, with special focus on community-based development, the empowerment of women, and the strengthening of ethical labour standards. Community-based developments bring about the inclusion and involvement of local people at different levels and steps, like production, processing, and marketing in the value chain of coconuts. It has been made amply clear and effectively documented in various research studies that rural women demonstrate relatively low indices on empowerment within rural settings, and it is primarily due to ethnic and socioeconomic factors such as early marriage, limited access to formal education, limited involvement in household and community decision-making processes, and unequal access to productive resources, services, decent employment, and markets.[107,108] Moreover, there exist various additional research studies emphasising and recommending women's empowerment at various levels and through focused intervention, such as imparting education, utilisation of technology, and awareness about fundamental rights and capacity building for employment generation. According to Wei *et al.*[108] and Heince *et al.*,[107] access to productive resources and strong social networks significantly improve women's empowerment and household food security.[107,109] Empowered women tend to participate more actively in decision-making, manage finances effectively, and prioritise family nutrition. Training, financial support, and business opportunities for women in the coconut industry promote gender equality and increase household income. Women-led businesses in coconut products can drive change in rural communities.[89]

The safety and welfare of labourers are also a major issue within the coconut industry because of the physically demanding and hazardous nature of activities like tree climbing, harvesting, and dehusking. As a result, injuries occur, most especially when done manually without making use of safety equipment and training.[110] Most of the workers lack access to medical care and work under informal conditions. The use of ergonomically developed devices, such as the coconut climber and mechanisation, can help in addressing the problems associated with manual labour and improve labour safety. Hence, investing in a training programme and facilitating availability of safe equipment is an indication of a commitment to responsible labour practice and protects the health of employees.

In the coconut industry, child labour remains a serious ethical issue, especially in smallholder and informal production systems. Due to its invisibility, as well as a variety of societal and economic factors, it becomes even more likely that there will be children at risk within the coconut sector, which turns into an issue of child labour and school dropouts. It leads these children to be exposed to physical harm and inhibits their education and growth. Addressing this problem requires strong enforcement of child labour law, awareness campaigns, access to quality education, and assistance to farmers to increase their income. Apart from this, ethical sourcing behaviour and certification schemes could prevent the use of child labour in coconut products, building a fairer and more sustainable industry. A socially and ethically responsible approach to the coconut industry ensures not only environmental and economic sustainability but also social equity, aligns efforts to eradicate poverty, ensure food security, achieve gender equality, and promotes decent work and uplifts the lives of millions. Women farmers seek government support for the program's sustainability in knowledge improvement, mechanisation, financing, and marketing.[109]

5.2. Supply chain and transparency

Supply chain and transparency refer to the open sharing and disclosure of social and environmental information within, and sometimes beyond, the supply chain. It encompasses the information's quality, quantity, clarity, and timeliness, and is enabled by Industry 4.0 technologies.[111] The food sector must maintain its global competitiveness and adaptability in a constantly changing market by leveraging cutting-edge technologies to enhance waste reduction efforts, optimise operational efficiency, and mitigate environmental impacts. Industries that adopt technologies like big data, simulation, blockchain, IoT, and sensor-based systems reliably achieve high operational performance.[112] In addition, the agri-food sector can achieve 23% cost reduction and nearly a 5% decrease in medium-level waste volumes by implementing these technologies.[113] These tools allow real-time tracking of product origin, quality, and environmental impact across the value chain. For instance, by incorporating IoT transport systems, storage conditions can be monitored continuously, and with immediate corrective actions, it guarantees resource utilisation, minimises waste, promotes ethical sourcing, fraud reduction, and fosters fair trade and product authenticity.

A significant breakthrough achieved by Papua New Guinea is 100% drone mapping of its coconut trees. Through this innovation, it is now possible to monitor the location, status, and density of the trees, thus enhancing programmes for harvest exploitation, control of pests, and replanting. As a result, Papua New Guinea leads the world in combining traditional farming methods with modern technology innovation to make a sustainable coconut industry.[114] Fatorachian *et al.*[115] reported that digitalisation contributes greatly to waste management in food supply chain operations by reducing carbon emissions. For example, optimisation of routes and improved resource allocation in supply chain operations led to a 33, 40, and 50% reduction in fuel consumption, transportation-related emissions, and operational emissions, respectively. Through digitalisation, it will be feasible for the coconut industry not only to make its supply chain transparent but also to gain trust and sustain its healthy growth.

5.3. Life cycle assessment

Life cycle assessment (LCA) is a systematic and comprehensive method used to evaluate the environmental impacts across all stages of a product, process, or service from cradle to grave. It helps in the identification of key hotspots across the product life cycle by calculating multiple environmental indicators, such as carbon emissions, biodiversity loss, and resource use. Therefore, it is considered an important tool for eco-innovation and is widely used as a key strategy and policy instrument for promoting sustainable development. By applying LCA, agro-industries can improve their eco-efficiency by developing more sustainable products and making informed, data-driven decisions to reduce their negative environmental impacts.[116] Therefore, LCA must be considered across all stages of the coconut processing industry, from cultivation and harvesting to processing, packaging, and distribution for comprehensive evaluation of environmental impacts. Putra *et al.*[117] conducted a LCA of VCO production and identified key environmental hotspots during the processing stage, where by-products such as coconut water, husk, and shell are discarded without reuse, leading to significant contributions to eutrophication (38 940.7 g N-eq) and global warming (10 672.5 g CO_2-eq). To lessen these effects, two approaches to waste valorisation were investigated. Nata de coco production reduced eutrophication to 598.6 g N-eq and global warming to 0.00049 g CO_2-eq, whereas coconut shell charcoal resulted in 649 g N-eq and 10.67 kg CO_2-eq, respectively. An analysis of the LCA of coconut farming and processing by Yani *et al.*[118] shows that energy-intensive operations and transportation have a major role in the carbon

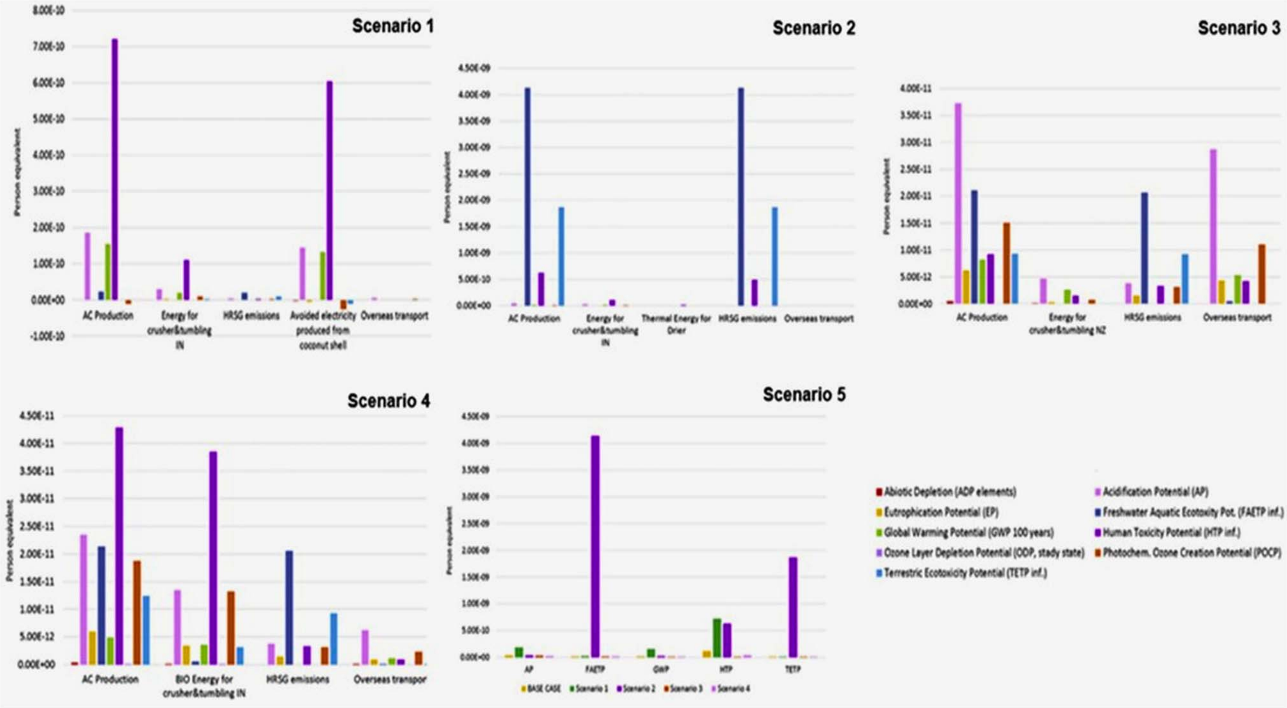

Fig. 4 LCA studies with different improvement strategies reproduced from ref. 119 with permission from [Elsevier] [A. Noemi, J. Lee and R. Clift, *Journal of Cleaner Production*, 2016, **125**, 68–77], copyright 2016.

footprint. Integrating coconut plantations with processing facilities can reduce emissions by up to 94.69% by minimising transportation fuel and treating pyrolysis smoke.

Various studies have reported that coconut shells are an effective precursor for activated carbon production and generally have lower environmental impacts than materials like wood. Arena *et al.*[119] conducted a LCA of activated carbon production from coconut shells in Indonesia, evaluating four scenarios with different energy sources, emission treatments, and production locations. The base case involved using shells only as feedstock with conventional electricity. In scenario 1, shell-based biofuel for on-site energy was considered. Similarly, scenario 2 assumes that distillate by-products (tar, gases) produced in carbonization are released untreated into the atmosphere, instead of being captured or used resulting in increased toxicity impacts, scenario 3 involved exporting shells to New Zealand, where renewable energy reduced emissions despite transport impacts, and scenario 4 focused on using shells locally as both feedstock and biofuel with renewable electricity, showing the lowest environmental impact overall. From Fig. 4, it is evident that in the case of environmental impacts and improvements, scenario 4 is the most sustainable, reducing global warming potential by 80% and human toxicity by 60% *versus* the base case. Therefore, the use of LCA is one of the key sustainable strategies in the coconut industry, serving as a tool for making decisions related to sustainable farming practices, waste valorisation, and low-impact processing technologies. Therefore, by implementing LCA from production to the consumer level, agro-industries such as the coconut industry can reduce their carbon footprint, increase resource-use efficiency, and develop evidence-based policies that support a sustainable transition.

6. Conclusion

Coconut is an extraordinary zero-waste resource, and the industry demonstrates a growing commitment to sustainability-oriented practices that aim to improve energy efficiency, reduce greenhouse gas emissions, and strengthen social responsibility. However, the industry still faces multiple challenges, including climate uncertainty, limited adoption of effective waste-utilisation methods, infrastructure and technical skills gaps, and inadequate global-level policy and marketing support. Therefore, there is an urgent need for the adoption of technologies that use resources more efficiently, cut down on chemical inputs, and make better use of waste, which can work towards increasing both sustainability and operational effectiveness. Furthermore, initiatives such as promoting gender equality, encouraging sustainable land-use practices, adopting biodegradable packaging, and implementing low-carbon technologies can support the industry's progress toward achieving the UN-SDGs. To drive this shift, decentralised waste processing, capacity building for farmers and processors, and public–private partnerships are essential. Additionally, future in-depth sustainability rating studies must be undertaken to ascertain regional challenges and formulate actionable, evidence-based solutions for local environments. This is a compelling demonstration of how sustainability may be integrated into one agricultural industry alone and, if replicated, could contribute to a climate-resilient, inclusive global food system.

Author contributions

A. D. Divate: writing – original draft. J. A. Moses: conceptualisation, supervision, writing – review and editing. S. Anandakumar: writing – review and editing. Sinija V. R.: writing – review and editing. N. Venkatachalapathy: writing – review and editing.

Conflicts of interest

There are no conflicts to declare.

Data availability

Data sharing not applicable. No new data were generated or analyzed in this study.

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