

Current situation, constraints and potential approaches in the utilisation and recycling of durian (*Durio spp.*) shell waste in Vietnam: a review

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ABSTRACT: This review aimed to investigate the durian industry in Vietnam regarding its current situation and constraints in terms of shell waste's utilisation and recycling, then emphasize potential approaches. In Vietnam, durian (*Durio spp.*) has recently become an important target for production, with approximately 150,000 hectares for cultivation, 1.2 million tons of annual harvest, and especially \$2.2 billion of export worth in 2023. However, the durian industry also generates a significant amount of shell waste, which is often discarded, leading to certain environmental concerns. The reviewing method was exploiting and discussing available literature, especially in the past five years, to illuminate an insight of the Vietnamese durian market, its existing issues, and recent solutions in the total utilisation of its shell for a more sustainable economy. Results indicated an increasing trend in cultivation areas, production, and export value. In addition, durian shell was reported as a rich source of materials for several industries, thus, leading to promising opportunities for a completed consumption of durian fruit. However, benefits come together with challenges, with standstill limitations in several aspects, e.g. insufficient technologies, infrastructures, policies, etc. Recently, innovative projects from several Asian countries were initiated with great potential, such as the production of: i) biodegradable plastics and packaging (Malaysia); ii) biochar (Thailand); iii) biogas (China); and iv) compost for organic agriculture (Vietnam). In addition, the possible exploitation of durian shells in other industries, such as nutraceuticals, pharmaceuticals, chemical, etc. was also highlighted. This review contributed important information for better choices and requirements in research and product development of durian shells for a greater contribution to sustainability and waste reduction in Vietnam.

KEY WORDS: *Durio spp.*, durian shell, utilisation, recycling

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I. INTRODUCTION

Vietnam's agriculture holds a significant position in the economy. In addition to being one of the world's leading rice exporters, the country is also developing the cultivation of fruit trees in large quantities and with a diverse variety. Among the fruit species with high economic value, durian is increasingly becoming popular and is consumed in large numbers, not only in the domestic market but also for export. Durian (*Durio spp.*) is a genus of the mallow family (*Malvaceae*). Currently, there are 30 identified species, of which about 9 bear edible fruit. *Durio zibethinus* is the species most widely found on the market. The distribution area of durian includes Southeast Asian countries, including Vietnam. In addition to direct consumption of the fruit flesh, durian can also be processed into many other products like ice cream, candy, and jams [1]. Durian production constitutes a vital agricultural sector in Vietnam, significantly contributing to the nation's economy. Recent data indicate that Vietnam has approximately 150,000 hectares devoted to durian cultivation in 2024,

primarily located in strategic growing regions, e.g. the Central Highlands, the Mekong Delta, the Southeastern areas. In addition, the annual production of Vietnamese durian has reached around 1.2 million tons, reflecting its rising market value both domestically and in international markets, particularly across Asia [2].

Durian production, both in Vietnam and globally, is currently substantial, and its market continues to rise. However, on average, the edible portion of a durian fruit constitutes only 15–30% of its total weight, while the outer rind, which accounts for 70–85%, is typically discarded as waste. This large amount of residual biomass poses significant environmental challenges [3]. The durian shell, often categorized as agricultural waste, also possesses distinctive physicochemical properties that enhance its potential for recycling and upcycling. Therefore, it has recently drawn huge attention toward the total utilisation in the durian industry, especially with recent initiatives for zero waste target in agriculture. In traditional medicine, durian shells are believed to have therapeutic properties, including the ability to clear heat, reduce internal fire, nourish yin, and moisten dryness. As a result, they are frequently used in Chinese folk medicine as a functional food to support the treatment of various health conditions [4]. Chemically, durian shells are also rich in cellulose and lignin, which are integral components of plant cell walls, providing structural integrity and mechanical strength [5]. These biopolymers render durian shells suitable for various applications, including the production of biodegradable composites, natural fibers, and bioactive compounds. Additionally, the physical characteristics of durian shells, such as their lightweight and fibrous nature, facilitate processing, making them amenable to diverse manufacturing processes [6]. The growing emphasis on sustainable waste management strategies presents significant opportunities for the effective utilization of durian shell waste, contributing to resource recovery efforts and the advancement of a circular economy within Vietnam.

However, the successful implementation of this innovative exploitation also heavily depends on a variety of factors: situation awareness of involving bodies, understanding of available technologies, optimizing of processing techniques, creating of supportive policy frameworks, and establishing of beneficial awareness of recycling and upcycling durian shells. Therefore, the purpose of this review was to explore and evaluate: i) the current situation of the durian industry and its shell waste issue in Vietnam; ii) its environmental and economic constraints; and iii) recent innovative approaches in the utilisation and recycling of durian shells together with clear-cut case studies.

II. CURRENT SITUATION OF THE DURIAN INDUSTRY IN VIETNAM

2.1 Durian cultivation and production

In Vietnam, durian trees are mainly concentrated in the Central Highlands, the Mekong Delta, the Southeast regions, and to a lesser extent in some provinces along the South Central Coast, with the cultivation method primarily reliant on natural processes [7]. In 2016, regarding production, the total area of durian cultivation in Vietnam was approximately 32,300 hectares, yielding 14.5 tons per hectare and producing 336,900 tons overall. The Central Highlands region contributed significantly, accounting for 24.7% (8,000 hectares) of the total cultivation area and 25.2% (over 85,000 tons of output) of the national durian production [8]. This trend of development keeps increasing rapidly over the past few years. According to the reported values on just the newly added growing areas, together with the efficiency and output of those areas, the values of only just 2022 (areas: 26,711 hectares; efficiency: 15.60 tons/hectare; output: 849,104 tons) already approached the same or even greater magnitude in comparison with the total amounts in 2016 [9].

Recently, in 2023, according to the statistical data from the Department of Crop Production (MARD), the durian-growing area in Vietnam now reached over 150,000 hectares, expressing an increase of approximately 20% and 500% in comparison with that of 2022 and 2016, respectively. In detail, the biggest cultivation area for durian is the Central Highlands (40.4%), followed by the Mekong Delta (34.6%), the Southeastern regions (19.4%), and the South Central Coastal regions (5.6%). The Central Highlands has surpassed the Mekong Delta to become the largest durian-producing region [10]. And recently, it is estimated that about 50% of the durian-growing area is currently being harvested (around 76,000 hectares), with the production in 2023 reaching nearly 1.2 million tons, increasing by an average of 15% annually. In the coming years, as the harvest area increases, Vietnam's durian production could potentially double [11].

Table I. Statistics on the 2022 newly added durian's cultivation areas, yield and output of some concentrated durian farming areas in Vietnam [9].

No.	Region / Province (in Vietnam)	Growing area (hectares)	Average efficiency (tons/hectare)	Output (tons)
	Central Highlands	14,216	16.03	336,430
1	Dak Lak	7,505	19.76	190,092
2	Lam Dong	3,019	13.30	106,158
	Mekong Delta	6,972	19.77	371,987
3	Tien Giang	3,259	26.46	278,249

4	Vinh Long	296	14.10	39,289
5	Can Tho	549	9.65	17,305
	South Eastern regions	4,788	10.43	122,899
6	Dong Nai	2,942	10.49	68,968
7	Binh Phuoc	1,037	9.25	21,804
8	Tay Ninh	445	13.24	24,845
	South Central Coast	731	6.72	17,772
9	Khanh Hoa	315	8.72	8,967
10	Binh Thuan	294	4.67	7,200
	TOTAL	26,711	15.60	849,104

2.2 Harvesting seasons in Vietnam

2.2.1 Central Highlands

In the Central Highlands, the varying altitudes at which durian is cultivated significantly impact the timing of both flowering and harvest. In Lam Dong Province, aside from Da Huoai District, which has a relatively warm climate comparable to that of Tan Phu District of Dong Nai Province where durian trees flower between December and January, allowing for an early harvest in April and May, other regions witness flowering between January and March, with the harvest occurring from July to August [12]. The lower temperatures in these regions prolong the duration from flowering to harvest for durians, extending this phase to as long as five months. Central Highlands region possesses a strategic advantage, as its harvest period extends later compared to both the Mekong Delta, Southeastern regions, and key durian-producing areas in Thailand and Malaysia, where harvesting occurs between July and October. Through the application of appropriate technical interventions to delay harvesting, the season can be extended until the end of November. Consequently, the market price of fresh durian in the Central Highlands tends to be higher than that of other durian-growing regions within the country [13].

2.2.2 The Mekong Delta, the Southeastern regions, and the South Central Coast

In the Mekong Delta, durian trees typically bloom between December and January, with the harvesting period occurring from April to May. This is attributed to the region's flat topography, elevated average temperatures, and shorter fruit maturation period. In regions of the Southeast and the South Central Coast, which includes key provinces such as Dong Nai and Khanh Hoa, the cultivation of crops follows a distinct seasonal pattern. The primary planting season generally begins in April and continues through June, taking advantage of the favorable climatic conditions during this period. As the crops mature, the harvest season typically commences in July and extends through September. The peak of the harvest, when crop yields are at their highest, usually occurs in August. This well-defined agricultural cycle is crucial for optimizing productivity in the region, ensuring that the timing of planting and harvesting aligns with the local environmental conditions [13].

2.3 Exporting status of durian from Vietnam

The variety of harvesting seasons in Vietnam allow a staggered supply of durians across the year, contributing to both domestic consumption and export opportunities. In 2023, the export value of Vietnamese durian reached \$2.2 billion. Vietnamese durian has a competitive advantage due to its year-round production, recently making a notable entry into the Chinese market. The city of Xishuangbanna (Yunnan Province, China) has emerged as a key hub for durian distribution in Southeast Asia. Situated near the border of Southeast Asia, the city's wholesale market for fruits and vegetables experiences significant activity, attracting both traders and tourists. A wide variety of durians from across the regions are transported to this depot, with an average sale of one ton of durian daily during the peak of tourist season. Despite a reduction in trade costs following the implementation of the RCEP agreement, durian prices have risen due to increasing demand from Chinese consumers [4].

The volume of fresh durian imports in China increased by 42.7% year-on-year in 2021, reaching 821,600 tons, while the value of these imports surged by 82.4%, totaling \$4.205 billion, making durian the leading imported fruit by both volume and value [14]. Since 2017, durian imports to China have nearly quadrupled, with projections indicating continued acceleration in the coming years. However, the increase in exports has also led to challenges, such as environmental concerns and overdependence on China. Moreover, negotiations are ongoing to expand exports to other regions of the world. There is significant potential for growth in durian-based processed products. Despite its relatively low production costs, the market faces challenges, mainly due to its dependence on a limited consumer base, with China being the primary market. Expanding market access remains crucial to overcome these limitations and sustain growth in the durian sector.

2.4 Shell waste issue of durian from Vietnam

In Vietnam, the rapid development of the durian industry, from cultivation areas to production, besides its massive benefits, has also put a tremendous pressure on the environment regarding agriculture waste due to its shells. And the more durian's production and export, the greater shell waste issue. An average value of 214,000 tons of durian shell waste was estimated to be discarded annually [15]. And the accumulation of shell waste in large numbers is a painful, yet inevitable, issue without being managed and treated properly. They are materials for environmental pollution, e.g. stink smell for the degradation process, blooming of harmful bacteria and fungi, etc. And this issue can subsequently lead to possible diseases within the community. In addition, keeping durian shell waste within the farm without any removing and cleaning activities can negatively impact durian trees themselves by the releasing of heat from the rotten process and the development of harmful organisms. However, any further removal action also cost farmers a substantial amount of money [16].

III. CONSTRAINTS IN THE UTILISATION OF DURIAN SHELL IN VIETNAM

3.1 Constraints in the availability of collecting and processing infrastructure

Internally, a significant barrier is the inadequate infrastructure available for collecting and processing of durian's shell waste, particularly in rural areas where durian cultivation is prevalent. Many of these regions lack the necessary facilities to efficiently manage large volumes of waste left over by the durian industry. In addition, the social awareness of shell utilisation is extremely limited for the case of durian. It is due to the fact that, in general, even the adoption of other agricultural by-product treatment technologies is also limited, especially in small-scale and household production. A survey in Thua Thien Hue Province in 2021 shows that only 15-30% of field by-products are reused, while most are burned. In addition, biogas use is low, with only 15% of households and 50% of farms adopting it. Proper composting practices are followed by just 15% of households and 50% of farms, involving the use of crop by-products and microorganisms [2]. This highlights the need for broader use of sustainable practices in small-scale agriculture. Consequently, this results in improper disposal methods, such as burning or dumping, rather than recycling. Moreover, there is a limited understanding among farmers and local stakeholders regarding the potential uses and benefits of recycling durian shells. This lack of awareness inhibits engagement in recycling initiatives, as individuals may not recognize the economic opportunities or environmental benefits associated with repurposing durian shell waste.

3.2 Constraints in financial status and capital investment

Financial constraints present another considerable obstacle, particularly for small-scale farmers who often operate on tight margins. These farmers may lack the capital needed to invest in recycling technologies or practices that could improve waste management and resource recovery. Large production facilities have established comprehensive production plans, from designing input materials to the treatment and recycling of by-products, following a circular economy model. This approach contrasts with small-scale, fragmented household operations, which often follow crowd-driven production trends. As a result, agricultural products frequently face surplus "rescue" situations, and agricultural by-products are largely neglected and undervalued [2]. The absence of targeted subsidies or financial incentives further exacerbates this issue, making it challenging for smaller stakeholders to transition to more sustainable practices. Additionally, the weak institutional capacity of local authorities can hinder effective waste management initiatives. Limited resources and personnel often result in inconsistent enforcement of existing regulations, creating uncertainty regarding compliance and implementation. Regulatory ambiguities regarding the classification and management of shell waste may also lead to confusion among stakeholders about their responsibilities, further complicating efforts to promote recycling and sustainability in agricultural waste management.

3.3 Constraints in policy

A lack of targeted policies specifically addressing agricultural waste management results in missed opportunities for resource recovery. The Law on Environmental Protection (LEP) 2020 promotes recycling and the circular economy but lacks specific guidelines for managing agricultural waste, such as durian shells, complicating prioritization in waste management frameworks [17]. Local enforcement suffers from limited resources, leading to inconsistent regulation, particularly in rural areas. While the National Strategy on Integrated Solid Waste Management (NSISWM) (2018-2025) aims for an 85% recycling rate for agricultural waste by 2025, it faces challenges due to inadequate infrastructure and ineffective collection systems [18]. Circular No. 36/2015/TT-BTNMT addresses hazardous waste but provides minimal guidance for organic waste, resulting in poor agricultural waste management practices [19]. Furthermore, the National Green Growth Strategy (Decision No. 491/QD-TTg) acknowledges the importance of sustainable growth but lacks concrete measures for supporting agricultural waste utilization, thereby limiting resource recovery opportunities, particularly in rural areas with restricted access to funding and technology [20].

Vietnam's laws and policies significantly limit effective agricultural waste management. Many frameworks lack specific guidelines, leading to implementation ambiguities. Challenges like inadequate infrastructure, insufficient support for small-scale farmers, and weak enforcement are compounded by market constraints and the absence of financial incentives for agricultural waste products, undermining resource recovery and sustainable practices [21]. Additionally, competition from other waste types for attention and resources can overshadow the recycling of durian shells [2].

IV. POTENTIAL APPROACHES IN THE UTILISATION AND RECYCLING OF DURIAN SHELL

Durian shells, which are typically discarded as agricultural waste, have shown potential as a sustainable feedstock for converting into valuable by-products through several emerging green technologies. These approaches not only help reduce waste but also contribute to a circular economy. The exploration of durian shell waste reveals its potential as a valuable resource across various sectors. Converting this by-product into biodegradable materials and biofuels addresses waste management issues while supporting sustainability. Additionally, extracting bioactive compounds for pharmaceuticals, cosmetics, and agriculture enhances its economic viability. Embracing these innovative uses promotes circular economy principles and contributes to more sustainable practices, positioning durian shell waste as a promising candidate for future resource recovery initiatives.

4.1 Renewable energy and agricultural benefits of pyrolysis

The potential energy obtained from durian biomass waste has been explored recently, focusing on its conversion into biochar via pyrolysis and hydrothermal carbonization, with various applications in catalysts, wastewater treatment, biocomposites, fertilizers, supercapacitor electrodes, and briquettes [22]. Pyrolysis is a thermochemical process of heating organic materials in the absence of oxygen, causing them to decompose into valuable products like biochar, bio-oil, and syngas [23]. When applied to durian shells, pyrolysis can yield biochar, a carbon-rich material useful as a soil amendment that improves soil health and sequesters carbon. It also produces bio-oil, which can serve as a potential biofuel or a source of chemicals for industrial applications, and syngas, a mixture of hydrogen and carbon monoxide that can be used as a fuel or chemical feedstock [24]. This process helps reduce agricultural waste while generating renewable energy. Additionally, biochar offers environmental benefits by enhancing soil fertility and acting as a carbon sink. However, difficulties include the high energy input required for pyrolysis and the need for subsequent refinement of bio-oil to make it commercially viable [25].

4.2 Fertilizers production using effective microorganisms and enzymatic treatment

Research indicates that incorporating nitrogen-rich sources, such as citrus peels, enhances the degradation process. Techniques including aerobic and vermicomposting have been explored to convert durian shell waste into valuable compost, thereby mitigating environmental pollution [26]. The efficacy of durian peel waste as an organic fertilizer has been scientifically supported, especially when combined with biological products derived from *Trichoderma* spp., which serve as enzymes that hydrolyze cellulose and lignocellulose in the durian shell. Studies have shown that using 5 kg of durian peel supplemented with 5 g of this biological product significantly accelerates the breakdown of the peel's lignocellulosic components [3]. The biological activity of *Trichoderma* spp. enhances the decomposition of organic matters and improves the nutrient profile of the resulting compost, fostering more sustainable agricultural practices. This transformation of agricultural waste into organic fertilizers enriches soil ecosystems with beneficial microorganisms and increases nutrient availability for plants [27]. Enzymatic treatments complement this approach by further breaking down complex polysaccharides in durian shells, such as cellulose and lignocellulose, into simpler sugars or other valuable by-products [28]. This enzymatic process can produce cellulosic ethanol for biofuels, biopolymers for biodegradable plastics, and nutritional supplements, as well as bio compost to improve soil health and fertility. Both biological and enzymatic treatments share the goal of converting durian waste into high-value products, contributing to energy-efficient, sustainable agricultural systems [29]. However, drawbacks such as enzyme costs, recycling, and process speeds must be addressed to optimize their potential [30]. Together, these approaches offer a comprehensive strategy for the valorization of durian waste, supporting both environmental and agricultural sustainability.

4.3 Nutraceuticals and pharmaceuticals

Durian waste offers significant potential for sustainable resource utilization, particularly through its husk, which demonstrates promise for biomedical applications and the production of value-added products, surpassing the traditional application of seeds as animal feed. A study investigated the secondary metabolites and antibacterial activity of durian peel ([31], [32]) extract to evaluate its potential as a natural antibacterial

agent in hand sanitizers. The findings revealed that the extract contains phytochemicals exhibiting antibacterial properties, effectively inhibiting the growth of *Escherichia coli*, *Salmonella typhosa*, and *Staphylococcus aureus* at a concentration of 1% [33].

Additionally, the antimicrobial activity of ethanol extract from durian shell was examined against *Streptococcus mutans* and *Enterococcus faecalis*, bacteria frequently implicated in dental caries and root canal infections. The extract demonstrated significant inhibitory effects on both *S. mutans* and *E. faecalis* at concentrations ranging from 6.25% to 50%, underscoring its potential as a preventive agent for dental caries. The bioactive compounds present in durian peel extract could be effectively incorporated into formulations such as mouthwash, root canal irrigation solutions, and topical applications [34].

In a related investigation, durian peel extract was formulated into an effervescent tablet as an alternative approach for the consumption of natural antioxidants. The antioxidant activity was assessed using the DPPH method, with the IC50 value measured to evaluate efficacy. Formula 4, comprising 30% durian peel extract, exhibited enhanced antioxidant activity compared to the other three formulations, achieving an IC50 value of 117.73 µg/mL, which is categorized as moderate antioxidant activity [35]. Summarily, these studies highlight the diverse bioactive potential of durian peel extract, emphasizing its applicability in health-related products and sustainable resource utilization.

4.4 Other potential applications

4.4.1 Chemical industry

Durian peel has been identified as an effective adsorbent for the purification of crude glycerol within the chemical industry. Research has focused on the utilization of durian peel as activated carbon for purifying acidified crude glycerol, achieved through acidification with concentrated acid and subsequent carbonization using 0.1N KOH. This process yielded an adsorbent with a carbon content of 80.6%, achieving a maximum purity of 96.26% at a 1:1 mole ratio and a 25% mass ratio [36].

4.4.2 Bioinsecticide

Research on the development of a bioinsecticide derived from durian fruit extract has also yielded promising results. Findings indicated that the optimal solvent ratio of ethanol to methanol was 2:1, when combined with ultrasonic assistance, resulting in the highest extraction efficiency of 12.8%. Liquid chromatography-tandem mass spectrometry (LC-MS/MS) analyses identified that alkaloid, flavonoid, and fatty acid compounds present in the durian extracts may contribute to larval mortality and can be further exploited as bioinsecticide [37].

4.4.3 Sustainable packaging from cellulose by-products

Cellulose fibers from the shells can be used as reinforcement material in biodegradable packaging or composites. Furthermore, durian peel can be effectively combined with other organic wastes, such as citrus peels, which are frequently composted to achieve sustainable waste management [6].

V. CASE STUDIES: GLOBAL AND LOCAL INNOVATIVE RESEARCH IN THE UTILISATION AND RECYCLING OF DURIAN SHELL

Durian shell's recycling and upcycling in countries like Malaysia, Thailand, China, and Vietnam have gained attention in various durian-producing countries due to their potential for reducing waste and promoting sustainability and demonstrated the potential of turning agricultural waste into valuable products. These studies showcased innovative solutions to the challenges posed by durian shell waste and highlighted the importance of collaboration between researchers, businesses, and governments for scaling up. Vietnam, in particular, stands to benefit from further investments in durian shell recycling technologies, with potential applications in activated carbon, organic compost, and even bioenergy [38]. Scaling up these initiatives could contribute to the country's sustainable development goals while providing new economic opportunities for farmers and businesses alike.

5.1 Malaysia: Production of biodegradable plastics and packaging [6]

Malaysia, one of the world's largest durian producers, has been at the forefront of recycling durian shells into biodegradable plastics. As a consequence, the development of bioplastics using cellulose extracted from durian shells from researchers of Taylor's University (Selangor, Malaysia) was announced with positive results. Through an innovative process, recycling durian shells were chemically treated for the obtaining of cellulose, and the further developed into thin bioplastic films. These films can be used as biodegradable packaging, offering a sustainable alternative to traditional single-use plastics. The biodegradable packaging maintains the strength and flexibility of conventional plastics while decomposing much faster in the environment. This research marked a significant achievement in the reduction of our reliance on petroleum-based plastics through its direct tackling of issues from both plastic pollution and agricultural waste in durian consumption. This initiative has attracted interest from the packaging and Fast-Moving Consumer Goods (FMCG) industries, driving the broader adoption of biodegradable materials. Key lessons from this project

highlight the importance of collaboration between academic institutions and businesses to foster innovation. However, for bioplastics from durian shells to be commercially viable on a large scale, further efforts in scaling up production and optimizing costs are necessary).

5.2 Thailand: Production of biochar [23]

Thailand, another major durian producer, has implemented several projects aimed at converting durian shells into biochar, a carbon-rich material used to improve soil health, store carbon, and generate energy. In a joint project between scientists from Phranakhon Rajabhat University (Bangkok, Thailand) and Rajamangala University of Technology (Pathum Thani, Thailand), durian shells were subjected to pyrolysis, a process in which biomass is heated in the absence of oxygen. This method produced biochar, a carbon-rich material used as a soil conditioner that enhances soil fertility and water retention. The excess heat generated during pyrolysis is also harnessed to produce energy. The adoption of biochar by Thai farmers has improved soil quality, reduced the need for chemical fertilizers, and increased crop yields. Additionally, the carbon sequestration properties of biochar help mitigate climate change by locking carbon in the soil for long periods. Biochar production has created new revenue streams for agricultural waste management businesses, turning waste into valuable products. This project demonstrates the potential of a circular economy model, benefiting both farmers and carbon management efforts. However, scaling up biochar production could be made more feasible through government support in the form of subsidies or incentives, particularly for small-scale farmers.

5.3 China: Production of biogas [39]

In China, where durian consumption has been growing rapidly, researchers from Beijing University of Chemical Technology (Beijing) reported positive outcomes in biogas production from anaerobic co-digestion of durian shell in order to reduce the environmental footprint of durian waste. Durian shells, along with other organic waste, were placed in anaerobic digesters where microorganisms broke down shells to methane-rich biogas. This biogas was captured and used as a renewable energy source for cooking and electricity generation in local communities, while the residual waste from the process was converted into organic compost. Therefore, this project provides an approach to significantly reduce landfill waste and supplies a renewable energy source to rural areas. In addition, it offers an alternative income stream for local farmers and communities, as the organic compost can be sold to agricultural sectors. The use of biogas has contributed to improved energy access in areas with limited or unreliable electricity grids. Key lessons from the project highlight that biogas production from durian shells is a practical, community-level solution for both waste management and energy generation, though awareness programs are needed to encourage wider adoption by farmers and communities.

5.4 Vietnam: Compost production for organic agriculture [3]

In Vietnam, scientists from the Vietnam National University of Forestry conducted the evaluation of organic fertilizers produced from durian's shells in Trang Bom District, Dong Nai Province to support the country's growing green agriculture sector. This initiative has contributed to sustainable farming practices by reducing chemical fertilizer use and promoting the use of natural alternatives in agriculture. The project composted durian shells along with other organic waste materials, such as food scraps and agricultural residues, to produce nutrient-rich organic fertilizers. The composting process was carefully managed under controlled conditions to efficiently break down the fibrous materials in the durian shells. The resulting compost can be sold to local farmers or used in organic farming cooperatives. This initiative has significantly contributed to reducing the use of chemical fertilizers, aligning with Vietnam's goals of promoting sustainable agricultural practices. Farmers using the organic compost have reported improved soil fertility, better crop yields, and lower farming costs. Additionally, the project has reduced the volume of durian waste going to landfills, helping to create cleaner urban and rural environments. Overall, composting durian shells offers a scalable solution for managing agricultural waste and supporting sustainable farming. Expanding the market for organic compost could further incentivize farmers to participate in similar composting initiatives.

VI. CONCLUSIONS AND RECOMMENDATIONS

In conclusion, the utilisation and recycling of shell waste is an inevitable future trend that help ensure the sustainability in growing for not only the durian industry but also the society. Therefore, innovative approaches for managing durian shells and turning them into a variety of value-added products are crucial for reducing environmental impact and fostering a circular economy in Vietnam. Despite existing limitations and constraints, both internal and external, the future outlook for durian shell utilisation and recycling in Vietnam is extremely promising, especially in fields such as sustainable agriculture, nutraceuticals, pharmaceuticals, renewable energy, etc. Recommendations for further improvements include: i) the optimization of technologies for durian shell's extraction and transformation, ii) the development of innovative value-added products and of targeted incentives for businesses engagement, such as tax breaks or subsidies, to encourage investment and

innovation; iii) the establishment of partnerships between government, industry stakeholders, and research institutions to facilitate the exploration of new technologies and methods for processing of durian shells; together with iv) the assessment of economic viability and affordability.

COMPETING INTERESTS

The authors declare no conflicts of interest.

AUTHOR CONTRIBUTIONS

Phu H. Le conceived the idea, provided support, and critically revised the manuscript. An D.X. Nguyen and Phuc N.T. Le structured the contents and wrote the manuscript. Anh N. Nguyen, Uyen P. Le, and Nghi B.P. Nguyen contributed to the finding of materials and proofreading. All authors read and approved the final manuscript.

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