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AGRICULTURAL WASTE VALORIZATION AND ITS IMPACT ON GREENHOUSE GAS REDUCTION IN SOUTHEAST ASIA

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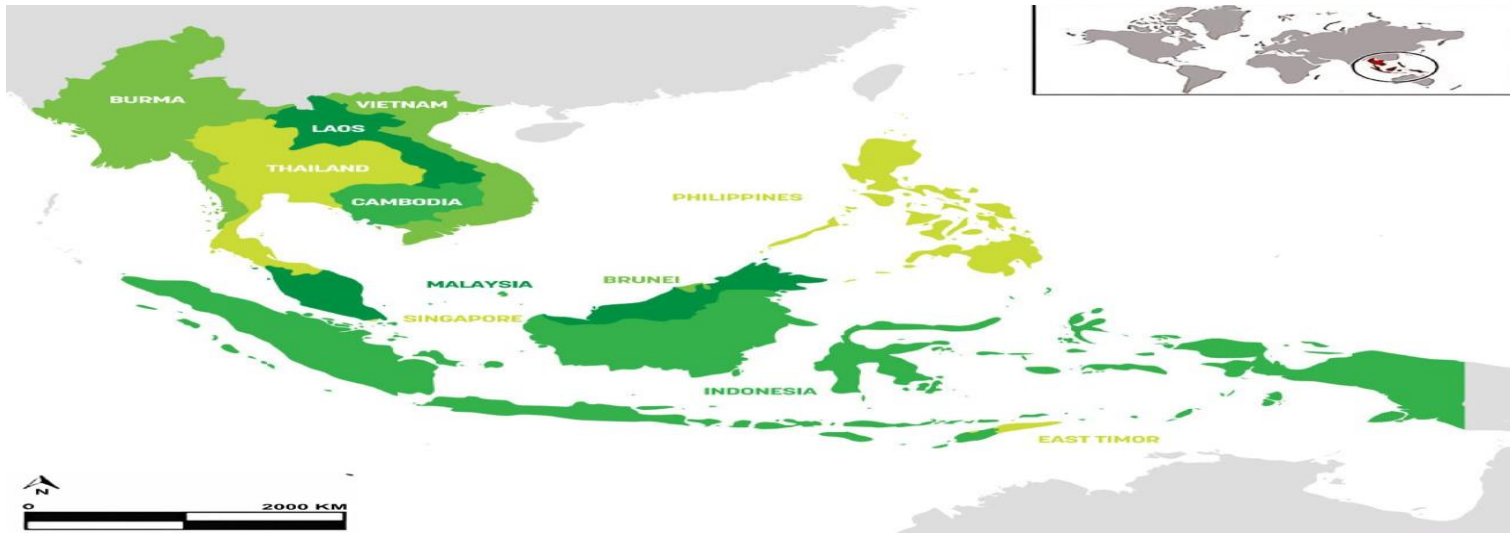
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Abstract: This paper aims to review and synthesize the existing literature on agricultural waste valorization in the Southeast Asian (SEA) region, with a focus on its potential to offset greenhouse gas (GHG) emissions. The SEA region generates abundant agricultural wastes from major commodity crops, such as: rice, palm oil, sugarcane, coconut, and corn, which present opportunities for valorization. The review found that countries like Indonesia, Malaysia, and Thailand have conducted several studies on agricultural waste valorization, exploring pathways such as bioenergy, value-added products, and soil amendments. However, only a few studies exist for some countries with high residue valorization potential, such as Vietnam and the Philippines. The reviewed literature showed a relationship between agricultural waste valorization and emissions that could contribute to air pollution, but no direct association was established with the associated GHG emissions. The abundance of agricultural residues across SEA presents opportunities for valorization to offset GHG emissions. However, effective valorization is hindered by challenges like open burning practices, logistical issues, and a lack of sustainable waste management strategies. This review highlights the need for further research to establish the direct relationship between agricultural waste valorization and GHG emissions reduction in the SEA region.

Keywords: Agricultural waste; Biomass; Valorization; Greenhouse gas; Southeast Asia

1. Introduction

Southeast Asia (SEA) is recognized as one of the most dynamic and diverse regions worldwide ^[1,2]. It is a geographic sub-region located in the Southeastern part of Asia, comprising eleven nations spanning from the areas southeast of the Indian subcontinent, southern China, and the Northwestern region of Australia ^[3] (**Figure 1**).



Geographically, the region is separated into “mainland” and “island” zones. The mainland zone includes Myanmar, Thailand, Laos, Cambodia, Vietnam, and Peninsular Malaysia; while the island zone encompasses Brunei, East Malaysia, Timor-Leste, Indonesia, the Philippines, and Singapore ^[4].

The agricultural sector plays a crucial role in the economies of Southeast Asian nations ^[6], making a significant contribution to the countries’ gross domestic product (GDP) and employment rates ^[7]. The demand for agricultural products is currently at an all-time high due to population growth ^[8], with substantial quantities of crops produced for both domestic consumption and export ^[9]. Many countries in the region are among the world’s top producers of agricultural commodities such as rice, sugarcane, palm oil, and coconut ^[10].

The high agricultural productivity in SEA generates significant quantities of underutilized residues ^[21]. A portion of the residue is incorporated back into the soil, while a certain amount is used for energy purposes; the remainder is either dumped in landfills or openly burned in fields ^[22]. Open burning of crop residues leads to the release of substantial amounts of air pollutants, such as particulate matter (PM), carbon monoxide (CO), volatile organic compounds (VOCs), black carbon (BC), and organic carbon (OC), as well as potent greenhouse gases (GHGs) like methane (CH₄), carbon dioxide (CO₂), nitrous oxide (N₂O), and small levels of nitrogen oxides (NO_x) and sulfur oxides (SO_x) ^[23].

GHG emissions are considered one of the primary root causes and most significant challenges in addressing climate change ^[6]. Agricultural burning, particularly when conducted on a large scale for commercial agriculture, is a leading source of CO₂ and GHG emissions ^[24,25]. Farmers often find the collection and transportation of residues from fields costly, making burning the most economical method for disposing of excessive residues ^[4,22,23,26]. SEA has been reported as one of the largest biomass-burning source regions globally ^[27,28] and has the highest per capita GHG emissions in the agriculture, forestry, and other land use (AFOLU) sectors in Asia ^[29].

Agricultural waste is often a valuable resource that can be repurposed or given to new uses ^[4]. However, despite their multiple applications and significant potential ^[26], when mismanaged, they not only contribute to GHG emissions in post-harvest activities ^[30] but also represent a missed opportunity for valorization into valuable

products. Nowadays, where the principles of sustainability and resource efficiency are paramount, the concept of a circular economy has emerged as a key approach for promoting sustainable resource utilization and minimizing waste generation ^[31].

Valorization, or the process of increasing the value, of agricultural wastes can transform these residues into high-value-added products, including biofuels, biochemicals, and biomaterials ^[32], offsetting GHG emissions while generating economic benefits. Currently, SEA has an abundance of agricultural waste generation due to high agricultural productivity, and several pathways for valorization exist in each country in the region.

This paper aims to review and synthesize the literature on agricultural waste valorization in the SEA region in the context of offsetting GHG emissions. Presently, other existing review articles in SEA are specific to individual countries, and there are no studies encompassing the valorization of agricultural wastes across the entire SEA region; hence, this review was undertaken. Sixty-five (65) papers were obtained from Google Scholar, including those indexed in Scopus and Clarivate databases, by searching for the following keywords: agricultural waste, valorization, agricultural residues, biomass, Southeast Asia from the year 2015–2024.

The review consists of three main subsections: (a) status, (b) challenges, and (c) future directions.

2. Status

The Southeast Asian region is endowed with abundant agricultural residues arising from the cultivation of major commodities like rice, oil palm, sugarcane, coconut, corn, cassava, and others.

Indonesia, being the largest producer and exporter of palm oil along with Malaysia, generates massive quantities of solid residues like empty fruit bunches (EFB), palm kernel shells (PKS), mesocarp fiber, fronds, and trunks ^[14,15,33]. Other major residues include rice straw, rice husk, sugarcane bagasse, cocoa pod waste, coconut shells/husks, and residues from banana and pineapple cultivation ^[1,10,12,34]. The availability of these diverse residue streams presents opportunities for valorization into bioenergy, biorefinery products, and soil amendments. Malaysia, the second-largest palm oil producer ^[35], faces waste management challenges ^[36] from the oil palm industry's EFB, PKS, fronds, and trunks ^[37–39]. It also generates residues from rice, coconut, pineapple, banana, durian, and sago starch production ^[22,34,40,41]. The government aims to capitalize on bioenergy from these abundant residues to reduce greenhouse gas emissions ^[42]. Thailand is a major producer of residues from sugarcane (bagasse, tops, leaves), rice (straw, husk), palm oil (kernels, EFB, trunks), rubber, teak, cassava, and tobacco cultivation ^[1,32,43]. Open burning of crop residues like rice straw and sugarcane trash is widespread, causing air pollution and transboundary haze events ^[26,32,44–46]. Valorization pathways like bioethanol production from molasses, cassava, and tobacco stalks are being explored ^[1,43,47]. Vietnam faces challenges with the open burning of rice straw, a common crop residue disposal practice ^[26,27,48]. Other residues include rice husks, bagasse, maize trash, cassava stems, peanut shells, coffee husks, and coconut shells ^[10]. Developing sustainable valorization routes for these residues can mitigate emissions and provide economic benefits. The Philippines generates abundant rice residues (straw, husk, bran) as a major producer, along with corn residues, coconut biomass, and sugarcane bagasse ^[1,13,49,50]. Open burning of residues like rice straw is prevalent, leading to emissions and health hazards ^[13,50]. Valorization into biochar, particle boards, and bioenergy represents potential solutions ^[13,51,52]. Cambodia heavily relies on rice cultivation, generating rice straw, husk, and other residues like corn cobs, cassava stalks, groundnut shells, and coconut shells ^[4,10,19]. Open burning of post-harvest straws is a traditional practice requiring sustainable residue management approaches ^[4]. Smaller nations like Brunei, Laos, and Myanmar have relatively lower biomass potential compared to regional agricultural giants ^[5,10,19]. However, residues from coconut, rice, corn, and cassava cultivation present opportunities for localized valorization efforts aligned with

largely agrarian economies. Singapore, being a compact island nation with negligible domestic agricultural production, can potentially import and utilize regional biomass residues like EFB from neighboring palm oil producers are biorefinery feedstock, leveraging its strategic location and status as a major oil refining hub ^[18]. their

3. Challenges

Despite the abundance of diverse agricultural residues across Southeast Asia, several challenges hinder their effective valorization into value-added products, bioenergy, and soil amendments. These challenges span technological, economic, social, institutional, and environmental domains. From a technical standpoint, issues related to biomass supply, including availability, scattered locations, and high moisture content, pose hurdles ^[12,56]. Logistical challenges, such as storage and transportation due to the low density and high volume of biomass residues, further compound the problem ^[56,58,59]. Additionally, the lack of accessible and reliable technologies, especially those tailored for tropical biomass feedstocks, and the shortage of technical expertise, particularly in small and medium enterprises (SMEs), impede progress ^[10,56]. Social awareness and responsibility barriers, such as the failure to raise public awareness about the importance of the biomass industry and its potential socio-economic benefits, hinder development ^[56,60].

Moreover, misconceptions about the benefits and losses from crop burning, along with long-standing established norms, contribute to the prevalence of open burning practices ^[4]. Institutional and policy barriers include gaps between academia and industry players, the absence of biomass monitoring and tracking systems, and the lack of agreement between policymakers and departments ^[1,56]. Additionally, the lack of preferential regulatory frameworks and institutional barriers impede the bioenergy transition in some countries ^[1,61]. Environmental considerations, such as the need to assess the full environmental impacts of biomass conversion technologies from cradle-to-grave, must also be addressed ^[56]. Furthermore, the open burning of agricultural residues contributes significantly to air pollution, particulate matter emissions, and the release of greenhouse gases, posing a significant environmental challenge ^[5,26,32].

4. Future directions

Several authors highlight the importance of integrating circular and sustainable agricultural practices as paramount for addressing agricultural waste and associated greenhouse gas emissions. Promoting alternative practices and technologies to replace open burning is crucial, including developing incentive policies and treatment/ recycling technologies ^[4,28], supporting smallholder farms to transition to sustainable practices, and improving residue collection and

Table 3 valorization technologies ^[28,58,62].

Embracing circular and sustainable agricultural practices, such as implementing good agricultural practices emphasizing waste minimization, reuse, recycling, and proper disposal; adopting circular agriculture principles; increasing emphasis on organic, bio-, and bioorganic fertilizers; and conducting field trials to explore biomass/fertilizers' potential for increasing soil carbon sequestration ^[12,37,63,64].

Effectively communicating and enforcing existing regulations prohibiting open burning, and developing databases and GIS maps to track residue availability and distribution ^[4], investigating residue conversion into energy through various processes, developing integrated biorefineries for efficient lignocellulosic biomass conversion, overcoming technical barriers in thermochemical and biochemical conversion of rice residues, and exploring the production of high-value products from rice biomass ^[1,4,65].

Conclusions

The Southeast Asian region generates abundant agricultural residues from major commodity crops like rice, palm oil, sugarcane, coconut, and corn, which present opportunities for valorization to offset greenhouse gas emissions. The reviewed literature has shown that countries like Indonesia, Malaysia, and Thailand have conducted numerous studies on various valorization pathways, including bioenergy, value-added products, and soil amendments; yet, research is limited for some countries in the region, especially those with high residue valorization potential, such as Vietnam and the Philippines. The available studies have indicated a relationship between agricultural waste valorization and emissions that could contribute to air pollution. Nevertheless, this review could not draw specific conclusions, as the studies did not establish a direct association with the related GHG emissions. Valorization of agricultural wastes is hindered by open burning practices, logistical issues, and a lack of sustainable waste management strategies. Overcoming these barriers could lead to significant environmental and economic benefits for the region. Moreover, further research is needed to better understand the direct relationship between agricultural waste valorization and greenhouse gas emissions reduction in SEA. Region-wide assessments and cross-country comparisons would provide insights to guide policymakers and stakeholders in developing strategies for sustainable agricultural waste valorization.

Author Contributions

Conceptualization, methodology, original draft. Z.N.; Review and supervision, G.L..

Conflict of Interest

The authors agreed to the publication of this manuscript version and declare that there are no conflicts of interest.

Data Availability Statement

The data analyzed in this review are studies available from cited published online sources. The review synthesized information from sixty-five (65) research articles and reports from Google Scholar, including those indexed in Scopus and Clarivate databases by searching for the following keywords: “agricultural waste”, “valorization”, “agricultural residues”, “biomass”, “Southeast Asia” for the period of 2015 to 2024. The specific sources are appropriately referenced throughout the manuscript and no new datasets were generated in this review.

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