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# Progress towards adopting low-carbon agriculture on peatlands for sustainable development in Indonesia

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**Abstract**. Indonesia, progressing towards sustainable development, faces the complex task of transitioning to low-carbon agriculture in peatlands, an essential part of broader sustainable objectives. Under the Paris Agreement, it targets a conditional 41% emission reduction, focusing on minimizing emissions from peat decomposition and fires within agricultural practices in peatlands. This paper explores the complexities and progress of low-carbon agriculture in peatlands, underscoring its significance in the larger sustainable development agenda. Our study reveals that current strategies to reduce carbon emissions in peatlands aim at restoring their natural waterlogged conditions. Yet, progress is hindered mainly due to an inadequate understanding of greenhouse gas emissions from peatlands and overlooking their unique features, which leads to overestimated emissions from agricultural use. For improved strategies, it's important to analyze successful existing sustainable practices and enhance understanding of peatland ecology. Techniques like the "Water Management Trinity," implemented since 1986, and eco-management emphasize the importance of using permanent water gates to maintain water levels optimal for both peat preservation and crop production. Over time, these practices modify peatland attributes, making emissions comparable to those from mineral soil, thus rendering low-carbon agriculture attainable. It's vital for stakeholders to assess emissions with updated data, incorporating detailed information on peatland characteristics and emissions. The journey towards low-carbon agriculture in Indonesia's peatlands is a complex endeavor necessitating the amalgamation of scientific research, sustainable practices, and socio-economic development. Adopting a holistic approach can strike a balance between agricultural productivity, peatland conservation, and climate change mitigation, fulfilling sustainable development goals in Indonesia and globally.

**Keywords:** Low carbon agriculture, peatland, water management, sustainable development

## 1. Introduction

Peatlands, covering about 8% of Indonesia's land area, represents one of the country's largest ecosystems [1]. For generations, these peatlands, especially in tide-affected coastal zones, have been integral to agricultural activities [2,3]. However, the agricultural utilization of peatlands brings forth sustainability challenges, notably due to the emission and sequestration dynamics of greenhouse gases (GHGs) that can impact global climate [4–6].

Transitioning from these environmental concerns, the role of agriculture in the economic sphere is equally pivotal. The agriculture sector plays a significant role in Indonesia's economy, contributing to approximately 13.22% of the country's Gross Domestic Product (GDP) in 2021 [7]. This percentage underscores the influence agriculture has on the country's financial stability and growth. Yet, intertwined with this economic significance is an environmental quandary. Research indicates that carbon stocks within peatlands range from 13.6 to 40.6 Gigatons (Gt) [8], even reaching 57.4 Gt at the highest estimates [9]. Such vast carbon reservoirs bring inherent risks, emphasizing the need for sustainable agricultural practices that not only minimize GHG emissions but also protect these carbon stores.

Considering Indonesia's commitment to the Paris Agreement, the nation has committed to an unconditional 29% emission reduction and a further conditional cut of 41% by 2045 [10]. Acknowledging the significant implications for the agriculture and FOLU (Forestry and Other Land Use) sectors, pioneering low-carbon agriculture emerges as a primary pathway to uphold these commitments. Key tenets of this strategy involve managing peat decomposition and fire prevention, both central to curtailing emissions from peatlands. Although decomposition, a natural process contrasted with aerobic accumulation, depends on oxygen for microbiological action, its role in carbon losses from peatlands, juxtaposed with fires, remains a topic of debate due to peatlands intricacies and its management [11]. Concurrently, regulatory measures dictate maintaining the water table at a steady 40 cm, irrespective of seasonal rainfall variations. Yet, current research shows a weak or even non-existent link between water table depth and $CO_2$ emissions [12]. Nonetheless, consistent water table management is pivotal to lessen fire risks, largely through preserving soil moisture [13].

In the broader context of sustainable development, especially on peatlands, the challenge lies in balancing careful resource utilization with the maximization of socio-economic benefits for humans [14]. Consequently, the notion of low-carbon agriculture on peatlands must incorporate a comprehensive view of both emission reduction and carbon sequestration, striving to achieve a net carbon sink. This approach emphasizes the dual goal of maintaining ecological integrity while also promoting economic productivity. By managing emissions and promoting carbon sequestration, peatlands can continue to serve as crucial carbon sinks, reducing the overall carbon footprint.

Simultaneously, the pursuit of low-carbon agriculture can foster more sustainable farming practices, which can support local economies, enhance food security, and contribute to a more sustainable future. The objective of this paper is to explore in greater detail the mechanics and advancements in low-carbon agriculture on peatlands, particularly within the broader context of sustainable development. To this end, a literature review was conducted to identify existing gaps and progress in the development of low-carbon agriculture on peatlands in Indonesia.

## 2. Mechanisms of carbon emission in peatlands

### *2.1. Development of tropical peatlands in Indonesia*

In their natural state, tropical peatlands exhibit a unique balance where the accumulation of organic matter consistently exceeds decomposition. The depth of accumulated organic matter, which constitutes the peatlands, varies globally - it's 30 cm in Canada, 40 cm in Russia, and extends to 50 cm in Indonesia [15]. This delicate balance facilitates the gradual formation and stabilization of peatland ecosystems. Four pivotal factors are integral to this process: a sustained influx of organic material, regular water supply, nutrient-poor conditions, and a topographical configuration that provides a basin for organic matter accumulation and water retention [16,17].

In Indonesia, the organic input to peatlands primarily comes from forest components like wood, leaves, branches, and roots [18]. This results in peat that is substantially composed of undecomposed woody material (Figure 1). Sabiham and Furukawa (1986) discovered that the composition of organic matter differs by layer within the peatlands: the bottom layer is predominantly made up of ferns, while the upper layers contain tropical forest species such as those from the *Eugenia*, *Palaquium*, and *Koompassia* genera [19]. In coastal areas, organic matter primarily derives from mangrove species. Hapsari et al. (2017) further analyzed that peatland's organic content traces back to peat swamp forests such as *Durio*, *Garcinia*, and *Sapotaceae*, mixed riverine forests including *Macaranga* and *Antidesma*, mangroves like *Rhizophoraceae*, and herbaceous plants [20]. This consistent influx of varied organic matter is vital for the formation and conservation of peatlands. To supersede the rate of decomposition, the quantity of this organic input must be substantial, ensuring the continuous accumulation of organic matter and preserving the unique ecological structure of the peatlands [20,21].

**Figure 1**. The material composition of tropical peatlands is non-homogeneous, primarily deriving from various tropical forest components [22].

Defined by a proximate water table, peatlands resonate with wetland attributes [15]. Primarily replenished by rainfall, this water supply anchors the inundated nature of peatlands and influences peat composition [23]. The saturation of the peatlands inhibits oxygen from permeating deeply into the soil, engendering an anoxic environment (lacking oxygen) that substantially slows the decomposition of organic material. Additionally, the final condition contributing to this unique ecosystem is its nutrient-poor status. Rainwater, the main source of water input, contains few nutrients. The water supply shaping the characteristics of Indonesian peatlands may differ from those in tropical peatlands in the Congo and Amazon regions [17]. The scarcity of nutrients, along with the anoxic conditions, curtails microbial activity, thereby further reducing the rate of organic matter decomposition.

In summary, the combination of several key factors contributes to the formation of peatlands. A substantial influx of organic material, persistent waterlogged conditions, and a nutrient-poor environment work in concert to create these unique ecosystems. The interplay of these elements is particularly evident in basin topographical areas, often situated between two rivers, where the physical geography supports the accumulation and retention of water and organic matter, fostering the development of peatlands.

### *2.2. Peatlands mechanism on emitting and dissolving carbon*

Peatlands consists of partially decomposed organic material with a specific decomposition rate and depth [24]. A significant part of this organic matter is comprised of complex carbon compounds primarily sourced from cell walls such as cellulose and lignin (Table 1) [25]. Organic molecules feature chains of carbon atoms linked together, forming the "backbone" of the molecule. These carbon chains, embellished with varying quantities of oxygen, hydrogen, nitrogen, phosphorus, and sulfur, are essential for the formation of simple sugars, amino acids, and more intricate molecules with elongated carbon chains or ring structures. The decomposition rate of these molecules is influenced by their structural configuration—occurring swiftly for sugars, starches, and proteins, at a moderate pace for cellulose, fats, waxes, and resins, and very gradually for lignin.

In agricultural endeavors on peatlands, many crops find it challenging to thrive in saturated or overly moist soil conditions. Consequently, drainage systems are commonly introduced to eliminate surplus water from the peatlands. Although these systems cater to the crops by averting root suffocation, they also depress the water table, revealing more organic matter to atmospheric oxygen. The now exposed peat undergoes decomposition, resembling the breakdown of typical litter, but at a decelerated pace due to peatlands' moisture-rich and nutrient-deficient nature. The general reaction governing the decomposition of organic matter is:

$$\text{Organic matter} + O_2 \rightarrow CO_2 + H_2O + \text{Nutrients} \quad (1)$$

The decomposition process releases a variety of byproducts, including $CO_2$, energy, water, nutrients beneficial for plants, and transformed organic carbon compounds [26].

**Table 1.** Partial composition of mature plant tissue and soil organic matter

| **Component** | Percent | |
|---|---|---|
| | Plant tissue | Soil organic matter |
| Cellulose | 20 – 50 | 2 - 10 |
| Hemicellulose | 10 – 30 | 0 – 2 |
| Lignin | 10 – 30 | 35 - 50 |
| Protein | 1 – 15 | 28 – 35 |
| Fats, waxes, etc | 1 - 8 | 1 - 8 |

The process of decomposition is predominantly propelled by microorganisms, with bacteria and fungi playing pivotal roles. These organisms release enzymes that fragment complex organic compounds into more rudimentary molecules. Consequently, some of the carbon in the organic matter merges with oxygen to produce $CO_2$, which is then expelled into the ambient environment. The decomposition process in peatlands can yield different results based on the presence or absence of oxygen. In an oxic environment (where oxygen is present), decomposition leads to the production of $CO_2$. This occurs as microorganisms interact with oxygen, initiating the breakdown of peatland's organic material and subsequently releasing $CO_2$. In anoxic conditions, typically seen in waterlogged peatlands, methane ($CH_4$) is produced instead [27]. Additionally, the use of fertilizers in agriculture, often applied to boost productivity in nutrient-deficient peatland soils, can stimulate microbiological activity, leading to more rapid decomposition and autotrophic respiration.

The continuous decomposition of dead matter and altered organic material leads to the formation of a more intricate substance called humus, a process termed as humification. In peatlands, the levels of humification are categorized as fibric (poorly decomposed), hemic (medium-decomposed), and sapric (well-decomposed) [28]. Microorganisms play a pivotal role in peat decomposition, facilitating both humification and mineralization, and subsequently converting carbon structures into modified carbon products within the soil matrix.

However, it's important to distinguish between the mechanisms of $CO_2$ emissions from decomposition and from fires. While it's generally understood that fires in peatlands result in the loss of organic material, the actual process involves several steps. First, the burning of biomass above the peat layer generates ash, which accumulates on the peat surface. This ash tends to be alkaline, with a pH ranging from 6 to 11.2, and an average pH of 8.8 [29]. The alkaline conditions resulting from the ash can dissolve peat material, leading to increased levels of Dissolved Organic Carbon (DOC). Studies have shown that the rate of DOC production rises with increased alkalinity [30]. Second, most of the hemic or sapric layers dissolve under these alkaline conditions, leaving behind mainly the fibric layer that is poorly decomposed. When dry, this fibric layer can easily catch fire and lead to smoldering combustion. Understanding these mechanisms is critical, especially when considering experiments involving controlled burns on sapric peatlands. Such studies have indicated that fires do not easily ignite in sapric layers [31]. Therefore, peatland fires contribute to carbon loss not only through combustion but also through the dissolution of organic matter into DOC in alkaline conditions.

## 3. The progress towards minimises carbon emission on peatlands

The Ministry of Environment and Forestry of the Republic of Indonesia (MoEF) has released an operational plan with the goal of achieving a net carbon sink by 2030 in the FOLU sectors, including agriculture [10]. One central element of this strategy involves peatlands, with a focus on reducing emissions caused by both peatland fires and the decomposition of peat's organic matter. To achieve this, the MoEF is implementing comprehensive water management and restoration techniques.

A key strategy for minimizing emissions involves restoring peatlands to their original, waterlogged, and anoxic conditions. However, this restoration method may not be entirely compatible with the demands of crop production. As such, it becomes critical to maintain a stable water table at a depth of 40 cm through effective water management techniques. This recommendation predominantly applies to areas designated for agricultural concessions, including palm oil and acacia plantations. Sustaining a water table depth of 40 cm in these zones is a complex endeavor, further complicated by inconsistent rainfall patterns. Despite these challenges, implementing these water management methods has the potential to substantially decrease emissions resulting from peat fires by the year 2030. Conversely, the reduction in emissions originating from peat decomposition could be less significant, underscoring the need for ongoing efforts to fine-tune and enhance these mitigation strategies.

When it comes to restoration efforts, measures implemented for the rewetting of degraded peatland areas outside of agricultural concessions have shown promising initial results [32]. These activities primarily aim to improve the health of peatlands, particularly through the rewetting of dried-out areas, which helps restore their ecological function. However, it's worth noting that these restoration efforts are neither entirely successful nor unsuccessful. One primary reason for this is that they focus predominantly on restoring the ecological function of peatlands, while the essential aspect of community empowerment in the sustainability dimension faces several challenges [33].

Additionally, peatlands used for agricultural purposes present a more challenging scenario [6]. The primary concern is the significant reduction of emissions arising solely from peat decomposition and fire prevention. Current strategies focus on maintaining high water table levels at 40 cm all year without considering the season; however, the relationship between water table levels and emission rates is not well-defined and must consider the role of nitrogen [33]. As a result, these initiatives should be supported by improved agricultural methods and in-depth research. Therefore, logically, efforts to minimize emissions should primarily address these root causes instead of peripheral factors.

Looking ahead to the IPCC (Intergovernmental Panel on Climate Change) Guidelines for National Greenhouse Gas Inventories [34], there is no definition for tropical peatlands in Southeast Asia that differs from tropical peatland in the Congo and Brazil, as well as from temperate peatlands. In the process of peatland organic matter decomposition, microbial activity will decrease in sapric when well decomposed due to the limited source of organic matter as food. The transformation from ‘poorly decomposed’ fibric to ‘well decomposed’ sapric will increase the bulk density of peatland. This factor is often neglected and becomes erroneous in calculating emission, especially using the subsidence method. The transformation mostly causes peatland to undergo a compaction and consolidation process, not entirely resulting in the ‘organic matter of peatland’ becoming lost to the atmosphere as $CO_2$. While subsidence is pivotal in the context of peatlands, it isn't synonymous with decomposition effects. As such, efficient mitigation strategies should separately address these unique yet interlinked processes to sustain peatland health efficiently. This incomplete logical framework makes the emission from peatland consistently higher.

Research by Jamili et al. (2021) found that the $CO_2$ flux only from bare peat is 11.1 ton C-$CO_2$ $ha^{-1}$ $yr^{-1}$, with total emission from peat with 14-year-old palm oil being 24.1 ton C-$CO_2$ $ha^{-1}$ $yr^{-1}$ [35]. In *Acacia crassicarpa* plantation, used for biomass production with a 4-5 year crop rotation, $CO_2$ emission ranges from 35.77 to 52.43 ton C-$CO_2$ $ha^{-1}$ $yr^{-1}$; omitting the influence of fine roots and litter, the emission from peat soil is 26.04 ton C-$CO_2$ $ha^{-1}$ $yr^{-1}$ [36]. For comparison, $CO_2$ emission from peatland, especially after years of use for agriculture, due to well-decomposed peatland, is similar to emissions from mineral soil. Research by Hendri et al. (2015) in Andisol soil in Bogor, Indonesia, with horticulture, found that the emission is 15.6 ton C-$CO_2$ $ha^{-1}$ $yr^{-1}$ and from bare Andisol soil, it is 7.32 ton C-$CO_2$ $ha^{-1}$ $yr^{-1}$ [37]. In Acrisol soil, with 12-year palm oil, the emission is 11.73 ton C-$CO_2$ $ha^{-1}$ $yr^{-1}$ [39]. Emissions from intact forest in peatland are 15.5 ton C-$CO_2$ $ha^{-1}$ $yr^{-1}$ [38].

Simultaneously, other research estimated the emissions from peatland to be higher, ranging from 73 to 121 ton $CO_2$ $ha^{-1}$ $yr^{-1}$ in palm oil [39,40]. This difference necessitates further research to provide rational explanations for the cause and method. Concurrently, a significant intake of organic matter correlates with robust biomass production via photosynthesis. Both photosynthesis and biomass contribute to plant respiration, resulting in $CO_2$ emissions [41]. Thus, even in their natural state, $CO_2$ emissions from forested peatland could be higher compared to peatland agriculture [38]. Hence, it is crucial to differentiate emissions originating solely from peat decomposition—considering the specific conditions of the peatland—from those produced by plant respiration during photosynthesis, bulk density, and carbon content.

The implication is that the IPCC and the operational plan of MoEF should be wiser in characterizing emission with newer data and incorporate more detail on peatlands characteristics and emissions. For instance, the emission factor on peatlands from the IPCC has no scientific justification in its establishment [42]. Hence, the current emission from peatlands is overestimated due to a lack of understanding of Indonesia's tropical peatlands characteristic change process and an excessive focus on highlighting CO2 emission. Gaining a deeper comprehension of the diverse emission sources might pave the way for more targeted mitigation approaches. This mitigation, through comprehension and comprehensive research, surely will improve the success rate of the operational plan for net carbon sink by 2030 for peatlands agriculture and contribute to sustainable development in Indonesia. This is because these emission issues could lead to many obstacles for sustainable agriculture practices on peatlands in Indonesia.

Lastly, current measures have not sufficiently tackled the implications of El Niño events. El Niño is consistently linked with a higher incidence of fires on peatlands. However, most fires on peatlands occur on unowned or unmanaged land, not under agricultural practices, especially within industrial plantations that have the resources to mitigate fire incidents. Although large enterprises may possess the capacity to adapt to these periodic shifts, smallholder farmers working on peatlands could encounter significant challenges. Future strategies should acknowledge these climate-related episodes and foresee their impacts on various stakeholders, particularly the more vulnerable smallholder farmers.

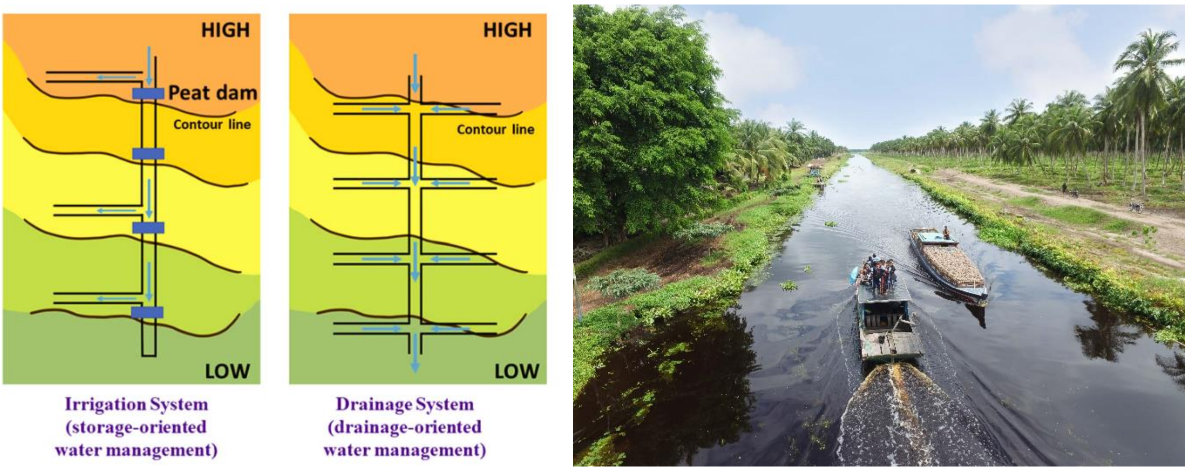
## 4. Strategy for achieving low-carbon agriculture on peatlands

The term "low carbon agriculture" is used in this context to encompass efforts to reduce both energy inputs and greenhouse gas emissions from agriculture, with advancements serving as a reliable indicator of enhanced environmental sustainability [43]. Although not all peatlands utilization for agriculture is successful, stakeholders often refer to the failure of the Mega Rice Project (MRP) in the mid-1990s due to the inadequacy of integrated and controlled water management [11,44]. Drainage excavation cut through the peat dome without appropriate water gate installations, subsequently undermining its hydrological function. Consequently, the aftermath was disastrous, turning the MRP area into a consistent source of fires and extensive degradation [45].

The importance of integrated water management provides the key to successful and sustainable peatlands utilization [11]. In the late 1990s, Ritzema et al. [46], highlighted the importance of water management to reserve water rather than drain it through drainage. Preliminary findings from our research suggest that employing a holistic water management approach, termed as the "Water Management Trinity" (WMT) and initially introduced in 1986, can markedly mitigate peatland degradation in coconut plantations while preserving their productivity [47]. As demonstrated in Pulau Burung District in Riau Province, the implementation of WMT manages to stabilize the water table with an annual average ranging from 48 cm to 49 cm [48]. This method of water management notably contributes to decreasing both land subsidence and carbon emissions, common repercussions of peatland degradation. Another sustainable concept, known as eco-management, which bears many similarities with WMT, also underscores the importance of stock-based water management [49,50]. Rather than draining the peatlands, an action that can hasten carbon release and impair the peat structure, this eco-conscious technique advocates for the conservation of water within the peatland system (Figure 2).

The concept of water conservation in agriculture emerged as an innovative paradigm for sustainable peatland management in the late 1990s [46,51], even though the principles had been integrated into the WMT system a decade earlier. This system fundamentally promotes a controlled and integrated approach to water management, employing permanent water gates to regulate water levels that cater to both peat conservation and crop agronomy needs. Canals function not as drainage conduits, but as reservoirs, embodying the essence of water conservation. The use of integrated water management, encompassing both the WMT and eco-management methodologies, emphasizes maintaining water levels to achieve a moist surface for oxic conditions.

The submerged layer beneath the average water table, covering the range between the highest and lowest water table levels, fosters anoxic conditions. Consequently, both the decomposition process and subsidence within the peatland are significantly minimized. This method aids in maintaining the natural water equilibrium, preserving the essential ecosystem functions and services for both industrial and smallholder agricultural endeavors. It then reduces $CO_2$ emissions and transitions into low carbon agriculture practices. Simultaneously, the low-carbon peatland agriculture strategy in Indonesia should focus on understanding peatland characteristics and processes, and on the application of integrated water management and sustainable agronomic practice. For effective low-carbon agriculture strategies, it's crucial to examine and learn from these longstanding applications of sustainable practices. By doing so, the fundamental concepts could be replicated and adapted to diverse contexts, contributing to the reduction of carbon emissions associated with peat decomposition.




(A) (B)

**Figure 2**. (A) The diagram depicts eco-management that employs stock-based water management through the use of water gates, taking elevation into consideration [49]. Meanwhile, (B) the reservoir canal in the WMT serves purposes such as water storage, agronomy, fire prevention, and transportation [52].

Finally, transitioning peatland agriculture to a low-carbon system necessitates a comprehensive and multifaceted approach. It is essential that the strategy also considers the multiple interacting stakeholders/ecological actors and the involvement of communities within the peatlands ecosystem [53]. Another possible strategy involves reducing excessive fertilizer use through the implementation of a nutrient cycling system, an approach already proven successful in an acacia plantation on the east coast of Sumatra [54]. Although integrated water management underscores the significance of both agricultural productivity and peat preservation, the current operational plans aiming to achieve a net carbon sink in the peatlands sector by 2030 still lack an in-depth understanding of the mechanisms through which peatlands emit greenhouse gases. This shortfall includes gaps in knowledge about the decomposition process and the impact of fires on peatlands. Such limitations have led to stagnant progress in minimizing carbon emissions and have resulted in restoration efforts that overlook the vital aspect of community empowerment. Hence, a low-carbon agriculture strategy for peatlands should be solidly anchored in water management, agronomic practices, an ecological understanding of peatlands, socio-economic considerations, stakeholder engagement, and insights from long-term studies.

The journey towards achieving low-carbon agriculture within Indonesia's peatlands, aimed at sustainable development, is a complex endeavor necessitating the integration of scientific research, sustainable practices, and socio-economic development. Through a comprehensive, well-informed, and inclusive approach, navigating these intricate challenges and making meaningful contributions to global sustainability goals becomes feasible. Effective emissions reduction is closely tied to both water management practices and socio-economic well-being, whether at the level of large enterprises or smallholder farms. By adopting such a comprehensive strategy, a balance between agricultural productivity, peatland conservation, and climate change mitigation can be achieved, not only in Indonesia but globally. Furthermore, any holistic approach to sustainable development must also prioritize socio-economic advancement and enhanced stakeholder engagement, both of which are vital for maintaining the ecological integrity of peatlands while acknowledging their agricultural significance and the livelihoods they sustain [55].

## 5. Conclusion

Developing low-carbon agriculture in Indonesia remains a substantial challenge. Despite effective reduction strategies, such as significantly mitigating peatland fires, the emissions from peatland decomposition continue to be debated due to the inherent complexity of the ecosystem processes involved. Specific conditions, particularly plant respiration and levels of humification, introduce bias into the estimations of emissions derived from peat decomposition, which are often overestimated due to a shortfall in understanding the complex nature of peatlands. Recent studies have found that emissions from peatlands are no different from those from mineral soil. In the context of sustainable development, the intricacy of achieving low-carbon agriculture extends beyond ecological dimensions to incorporate socio-economic aspects. To address this challenge effectively, the adoption of a comprehensive strategy is essential. This strategy should be rooted in rigorous research and development to identify and optimize practices from existing sustainable initiatives on peatlands that can reduce emissions without compromising agricultural productivity or the health of peatland ecosystems. Acknowledging and learning from existing sustainable practices, both locally and globally, can offer valuable insights and practical solutions for managing peatland agriculture in Indonesia.

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