

Estimation of Carbon Dioxide Emission and Sequestration from the Cradle-to-Grave Life Cycle of Bioethanol from Nipa Palm (*Nypa fruticans*) Sap

Muhammad Syukur Sarfat^{1*} and Andi Afandi²

¹Department of Agroindustrial Engineering, Faculty of Agricultural Technology, 16680 IPB University, Dramaga Bogor, Indonesia

²Center for Coastal and Marine Resources Studies, 16127 IPB University, Padjajaran Bogor, Indonesia

Abstract. The increasing demand for renewable energy has driven research into sustainable biofuel alternatives. This study evaluates the carbon balance of bioethanol produced from the sap of the Nipa palm (*Nypa fruticans*), a mangrove species with significant carbon sequestration potential. A cradle-to-grave life cycle assessment was conducted to estimate the total carbon dioxide (CO₂) emissions from bioethanol production and compare it with the CO₂ absorbed by the Nipa palm. The assessment covered emissions from transportation, fermentation, distillation, and distribution. The findings show that Nipa palms exhibit a substantial CO₂ sequestration capacity, averaging 21,785 kg CO₂/ha/year. The gate-to-gate emissions for producing 95% hydrous ethanol (H95F) and 99% hydrous ethanol (H99F) were calculated to be 1,075.91 kg CO₂/ha and 11,552.94 kg CO₂/ha, respectively. By comparing emissions against sequestration, the study reveals a significant positive carbon balance. The net balance for H95F production was -20,709.09 kg CO₂/ha/year, and for H99F, it was -10,232.06 kg CO₂/ha/year. This indicates that the bioethanol production system from Nipa sap is not only carbon neutral but carbon negative, as the Nipa palm cultivation absorbs more CO₂ than the entire production process emits. Furthermore, compared to gasoline, which emits approximately 2.91 kg CO₂-eq per liter, Nipa bioethanol presents a much lower carbon footprint. These results underscore the potential of Nipa palm bioethanol as a sustainable and environmentally beneficial fuel source that contributes to mitigating climate change by reducing greenhouse gas concentrations.

1 Background

Nipa palm, or *Nypa fruticans*, is a type of mangrove with significant potential for carbon dioxide (CO₂) absorption and carbon storage. Research indicates that nipa not only functions

* Corresponding author: msyukursarfat@apps.ipb.ac.id

as protective coastal vegetation but also plays a crucial role in climate change mitigation through photosynthesis. Nipa plants are vital in mangrove ecosystems due to their high carbon absorption capacity and the potential to produce activated carbon from their husks. With these characteristics, nipa can be a natural solution for climate change mitigation efforts and improved environmental management. Further research is needed to explore the full potential of this plant in the context of sustainability and environmental protection.

Nipa palm can store substantial carbon stocks. In a study comparing carbon stocks between *Nypa fruticans* and *Sonneratia alba*, nipa was found to have higher carbon stocks in several locations. For instance, at a particular station, nipa could store up to 7.06 tons/ha, while *S. alba* only reached 0.30 tons/ha [1]. Research Irmayeni et al. [2] also showed that the average nipa biomass is 9.64 tons/ha, with carbon storage reaching 4.82 tons/ha. This reflects the nipa plant's ability to store carbon in the form of biomass, which can help reduce CO₂ concentrations in the atmosphere. The larger the tree diameter, the higher its density, and the greater the biomass, the more carbon stock is stored [3]. Essentially, biomass is composed of several components such as cellulose, hemicellulose, lignin, starch, and protein. Woody trees generally have higher lignin and cellulose content compared to shrubs, so lignocellulosic plants have a higher potential for biomass content [4] will be produced, leading to greater potential biomass. In general, carbon stock has a positive correlation with the diameter and total length of the nipa palm. The positive carbon correlation of tree parts is greater in architecture with petiole length compared to average diameter. This positive correlation implies that an increase in petiole length will be followed by an increase in carbon in each part of the tree.

Nipa also demonstrates remarkable CO₂ absorption capabilities. The average total CO₂ absorption for nipa can reach 25.88 tons/ha, significantly higher than other mangrove species. Photosynthesis in nipa allows the plant to convert CO₂ into carbohydrates, which are stored in various parts of the plant such as leaves, stems, and roots [1]. Research Irmayeni et al. [2] also indicated that the average CO₂ absorption of nipa plants reached 17.69 tons CO₂-eq/ha. This reflects the nipa plant's ability to help reduce CO₂ concentrations in the atmosphere. It also shows that nipa has good potential for absorbing greenhouse gases and storing carbon in biomass. In the western part of Segara Anakan, Cilacap, nipa plants are known to have carbon storage of 10.38-25.4 tons C/ha [3,5]. Meanwhile, in the Ijo River Estuary, Ayah Village, Kebumen, nipa plants store 43.92 tons C/ha. Other studies outside Java also show nipa plant carbon storage in Riau at 38.10 tons C/ha, and Papua New Guinea and Northern Australia mention that nipa plant biomass ranges from 36.5-55.7 tons/ha, or equivalent to 17.16 and 26.18 tons C/ha [3,6]. Studies in Thailand also mention that nipa plants have the highest above-ground biomass (AGB) of 83 tons C/ha, equivalent to 39.1 tons C/ha of carbon storage [7,8].

Factors affecting CO₂ absorption by nipa plants are as follows: (1) Density and Diameter: The CO₂ absorption capacity of nipa plants is influenced by factors such as plant density and stem diameter. The larger the diameter and the denser the plant growth, the higher its CO₂ absorption capacity; and (2) Growing Environment: Environmental conditions such as water salinity and soil quality can also affect the effectiveness of CO₂ absorption by nipa plants. These plants generally grow in coastal areas with brackish water conditions that support their growth [1].

Based on the illustration above, nipa plants have significant potential in CO₂ absorption and carbon storage, making them an important component in mangrove ecosystems and climate change mitigation efforts. With relatively high biomass and the ability to adapt to coastal environments, nipa contributes to the reduction of greenhouse gas emissions through effective carbon sequestration. Nipa plants absorb CO₂ through photosynthesis that occurs in the leaves, where sunlight is used to convert CO₂ into carbohydrates. These carbohydrates are then distributed throughout the plant, including stems and roots, where most of the carbon

is stored [1,3]. Additionally, carbon sequestration also occurs in nipa plants, where this process stores carbon in plant biomass and soil substrate, which helps reduce CO₂ concentrations in the atmosphere [2].

Based on the illustration above, this study evaluates the carbon balance of bioethanol produced from the sap of the Nipa palm (*Nypa fruticans*), a mangrove species with significant carbon sequestration potential. A cradle-to-grave life cycle assessment was conducted to estimate the total carbon dioxide (CO₂) emissions from bioethanol production and compare it with the CO₂ absorbed by the Nipa palm. The assessment covered emissions from transportation, fermentation, distillation, and distribution.

2 Methodology

2.1 The estimation of CO₂ emissions from nipa sap bioethanol production

The calculation of CO₂ emissions from nipa sap bioethanol production involves several stages, from raw material collection to the distribution of the final product. Each stage has different emission sources, such as the use of fossil fuels in sap transportation, CO₂ emissions from the fermentation of sugar into ethanol (which is considered carbon neutral as it originates from biomass), energy consumption during the distillation and purification of bioethanol, as well as the transportation and use of the bioethanol product. The general formula used is:

$$E_{total} = E_{transportation} + E_{fermentation} + E_{distillation} + E_{distribution} + E_{usage} \quad (1)$$

Where, $E_{transportation}$ includes emissions from vehicles during the transportation of nipa sap from the plantation to the bioethanol production facility, $E_{fermentation}$ refers to emissions from biological CO₂ release, $E_{distillation}$ refers to emissions arising during the distillation process and is calculated based on energy consumption per liter of bioethanol produced, $E_{distribution}$ includes emissions from vehicles transporting bioethanol to end-users, and E_{usage} covers emissions generated during the use of bioethanol as fuel. The final result is converted into kilograms of CO₂ per liter of bioethanol to allow comparison with fossil fuels (gasoline). Additional emissions from the production of fossil fuels used in the process also need to be considered to obtain the total emissions.

2.2 The estimation of carbon balance

The carbon balance estimation is calculated based on the difference between the amount of CO₂ produced during bioethanol production from nipa sap and the CO₂ absorption by nipa plants. The carbon balance estimation is performed until a CO₂ value (in kg) per hectare of nipa plants per year (kg/ha/year) is obtained.

As a basis for calculation, nipa sap production figures from a study by [9] are used as a reference for comparison. One tapped nipa fruit stalk can yield 0.4 – 1.2 L/day, and the tapping period is 100 days/year. For a population of 1000 nipa palms/Ha, 50,000 – 100,000 L/Ha/year can be produced, with the lowest nipa sap production calculated at 0.5 L/day and the highest at 1.0 L/day. In this study, the following formulas adopted from [10] are used to estimate the potential nipa sap production (L/Ha/year):

$$P \text{ Sap}(\text{lowest}) = (0.1 \text{ liter} \times 1000 \text{ trees/Ha}) \times 100 \text{ days} \quad (2)$$

$$P \text{ Sap}(\text{highest}) = (0.5 \text{ liter} \times 1000 \text{ trees/Ha}) \times 100 \text{ days} \quad (3)$$

The density of nipa sap ranges from 0.790 – 0.793 g/cm³ or 0.790 – 0.793 kg/L [11], while the density of bioethanol from nipa sap is adopted from the density of bioethanol from aren sap, which is 0.8413 kg/L [12]. This approximation is considered reasonable as both aren and nipa sap-derived bioethanols undergo similar fermentation and distillation processes, producing ethanol-water mixtures with comparable compositions. Both feedstocks are tropical palm saps with similar initial sugar profiles (primarily sucrose, glucose, and fructose), which upon fermentation and distillation to 95% or 99% purity, yield bioethanol with similar physical properties. However, we acknowledge this as a limitation of the current study. Direct experimental measurement of nipa bioethanol density across different purification levels would provide greater precision and is recommended for future research to refine emission calculations.

3 Results and Discussions

3.1 The estimation of CO₂ emissions from nipa sap bioethanol production

Research by Mateo et al. [13] indicates that nipa-based bioethanol, Hydrous ethanol as pure engine fuel (95% ethanol) (H95F) and Hydrous ethanol as pure engine fuel (99% ethanol) (H99F), can function as renewable pure engine fuels, with carbon footprints of 0.2353 and 2.633 kg CO₂-eq per liter of bioethanol, respectively, within a Gate-to-Gate study scope. The purification or dehydration of bioethanol to reach 99% purity certainly requires high energy. According to Mateo et al. [13], achieving H99F requires a significant amount of additional electrical energy during the dehydration process, contributing 1.82 kg CO₂-eq per liter of bioethanol to greenhouse gas emissions. This is much higher compared to the purification or distillation of bioethanol to meet H95F standards, which only contributes 0.13 kg CO₂-eq per liter of bioethanol to greenhouse gas emissions.

The findings of Mateo et al. [13] demonstrate the potential of nipa bioethanol as a clean and sustainable energy solution. However, it is recommended that ethanol yield and the distillation process be further improved, and pure ethanol be explored as an alternative fuel for hybrid vehicles as 100% renewable vehicles. Although pure ethanol as an engine fuel for SI engines was found to be an alternative to fossil fuels, hydrous bioethanol is currently more recommended as a fuel blend rather than as a pure engine fuel due to an observable decrease in fuel economy of about 45% based on these research results. Studies on how to mechanize the sap collection process to enhance nipa-based bioethanol processes in terms of required volume, increase ethanol yield, and improve distillation efficiency should be conducted to maximize the full potential of *Nipa fruticans* as a bioethanol feedstock. Furthermore, the cost-effectiveness of nipa bioethanol and its lower carbon footprint compared to fermented sugar bioethanol strengthen its promise as a sustainable and environmentally friendly biofuel alternative [13]. Additionally, Mateo et al. [13] also stated that nipa-based hydrous bioethanol serves as an alternative to fossil fuels and as a pure engine fuel for gasoline engines with comparable engine performance, better combustion, and an A/F (Air-Fuel Ratio) as implied by higher CO₂ emissions and lower HC and O₂.

The greenhouse gas emissions in a Cradle-to-Grave scope for gasoline per 100 km of driving is 36.1 kg CO₂-eq, which is an accumulation of a series of processes: crude oil extraction process at 0.724 kg CO₂-eq, refinery process at 1.850 kg CO₂-eq, gasoline combustion process at 33.5 kg CO₂-eq, and transportation process at 0.06 kg CO₂-eq [14]. To travel 100 km using the Urban Driving Cycle (780 seconds) plus the Extra Urban Driving Cycle (420 seconds) consumes 12.4 liters of gasoline. This means that one liter of gasoline contributes 2.91 kg CO₂-eq of greenhouse gas emissions in a Cradle-to-Grave scope. Comparing bioethanol and gasoline, the greenhouse gas emissions per liter contributed by

gasoline are greater than those contributed by bioethanol, with a ratio of 12.37:1 for H95F and 1.09:1 for H99F.

If the identification is expanded to consider the nipa plant's high carbon absorption capacity, then the amount of greenhouse gas emissions imposed on the environment from the use of nipa-based bioethanol will undoubtedly be lower. This is because the greenhouse gas emissions imposed on the environment during bioethanol production and the use of bioethanol as a gasoline substitute will be reabsorbed by nipa plants for their growth and reproduction. This aligns with [15], who state that the use of bioethanol from nipa sap has a positive impact on the carbon balance. Nipa plants absorb CO₂ from the atmosphere during their growth, which helps reduce greenhouse gas concentrations, and when bioethanol is burned as fuel, the CO₂ emissions produced are comparable to the amount of CO₂ absorbed by the plants during photosynthesis, creating a balanced carbon cycle.

The use of fossil fuels such as gasoline and diesel is a primary source for meeting global energy needs. The results of this identification can provide a basis for comparison for future alternative fuel assessments that the Indonesian Government can propose to reduce oil dependency. Other alternative fuels that yield better environmental performance compared to gasoline can be considered as options to diversify Indonesia's energy mix.

High consumption of fossil fuels has significant negative impacts on the environment, including increased greenhouse gas emissions, air pollution, and decreased human health quality. Bioethanol can be one of the more environmentally friendly fuel alternatives. Bioethanol, which can be produced from various biomass sources such as nipa plants, has the potential to replace part of the fossil fuel usage.

In general, bioethanol produces lower CO₂, carbon monoxide (CO), and hydrocarbon (HC) emissions compared to fossil fuels. This indicates that bioethanol has great potential in reducing air pollution and negative environmental impacts. According to research by [16], bioethanol can significantly suppress CO and HC emissions. One of the main reasons is that bioethanol has a higher oxygen content than fossil fuels. When bioethanol is added to a fuel mixture, this oxygen content can increase the efficiency of the combustion process, resulting in fewer residual gases from incomplete combustion [17].

Moreover, although bioethanol still produces CO₂ during the combustion process, the amount of CO₂ produced is much less than from fossil fuels. One of the main advantages of bioethanol is its oxygen content, which reaches 35%, contributing to combustion efficiency and air pollution reduction. The oxygen content in bioethanol helps increase the efficiency of the combustion process. With more oxygen available, combustion becomes more complete, resulting in fewer harmful gas emissions such as carbon monoxide (CO) and hydrocarbons (HC). In some studies, the use of bioethanol even shows a decrease in CO emissions by up to 25% compared to fossil fuels [18,19]. Bioethanol is not only cleaner in terms of combustion but also has the potential to reduce overall air pollution. By simply mixing 3% bioethanol into conventional fuel, carbon monoxide emissions can drop to 1.3%, showing that bioethanol can serve as an effective solution for reducing air pollutants. Additionally, because bioethanol is made from natural materials, it also has a lower impact on climate change compared to fossil fuels [18].

Higher combustion efficiency means less fuel is wasted as harmful emissions. With lower carbon dioxide emissions, bioethanol can contribute to reducing the greenhouse gas effect, which is the main cause of global warming. In addition to CO₂, the use of bioethanol also results in lower emissions of other harmful compounds, such as nitrogen oxides (NO_x), sulfur dioxide (SO₂), and fine particulates. This makes bioethanol a more environmentally friendly fuel compared to fossil fuels. A table comparing CO₂, CO, and HC emissions produced by nipa bioethanol and fossil fuels can be seen in Table 1.

Table 1. Comparison of CO₂, CO, and HC emissions between bioethanol and fossil fuels.

Fuel Type	CO ₂ Emissions	CO Emissions	HC Emissions
Bioethanol	Lower	Lower	Lower
Gasoline	Higher	Higher	Higher

Source: [16]

As a renewable fuel, bioethanol has many environmental advantages. The production and use of bioethanol contribute to the reduction of greenhouse gas emissions. The combustion of bioethanol produces carbon dioxide (CO₂) that can be reabsorbed by plants, creating a more balanced carbon cycle. Thus, bioethanol not only reduces dependence on fossil fuels but also helps maintain overall air quality and the environment. Overall, bioethanol offers an environmentally friendly and efficient alternative to fossil fuels, with significant benefits in terms of emission reduction and air quality improvement [18,19].

However, there are challenges that need to be addressed in the use of bioethanol. One drawback is that incomplete combustion of bioethanol can produce aldehyde compounds such as formaldehyde, which are pollutants. Formaldehyde is known as a chemical compound that is harmful to human health due to its carcinogenic nature and its ability to damage the respiratory system if exposed in large quantities. This issue highlights that while bioethanol has many advantages in terms of emission reduction, there are still technical challenges that must be overcome to ensure complete combustion of bioethanol. Therefore, the development of more efficient and cleaner combustion technology is a top priority in optimizing the potential of bioethanol as a sustainable alternative fuel.

The choice between H95F (95% ethanol) and H99F (99% ethanol) involves critical trade-offs between environmental impact, production costs, and end-use applications. Our analysis shows that H99F production requires significantly higher energy input during dehydration, contributing 1.82 kg CO₂-eq per liter compared to only 0.13 kg CO₂-eq per liter for H95F [13]. This results in H99F having 11.2 times higher gate-to-gate emissions than H95F (2.633 vs. 0.2353 kg CO₂-eq per liter).

From a commercial perspective, H95F (hydrous ethanol) is recommended for most applications, particularly for: (1) Flex-fuel vehicles that can operate on high ethanol blends (E85-E95); (2) Ethanol-gasoline blends up to E20-E30 for conventional vehicles; (3) Industrial applications where absolute purity is not critical; and (4) Markets prioritizing environmental performance and lower carbon footprint.

H99F (anhydrous ethanol) is only necessary for: (1) High-percentage blends (E85-E100) in standard gasoline engines that require anhydrous ethanol to prevent phase separation; (2) Specific industrial processes requiring water-free ethanol; and (3) Regulatory requirements in certain markets mandating anhydrous ethanol for fuel blending.

The study by Mateo et al. [13] found that while pure ethanol can function as engine fuel, hydrous bioethanol (H95F) is currently more recommended due to better cost-effectiveness and lower environmental impact. Although H95F results in approximately 45% reduction in fuel economy compared to gasoline, this is offset by its significantly lower carbon footprint (12.37:1 ratio compared to gasoline) and lower production emissions. For nipa bioethanol commercialization in Indonesia and similar tropical regions, H95F should be the primary product for the following reasons: (1) Environmental advantage: 10.9 times lower emissions than H99F; (2) Economic efficiency: Lower energy and operational costs; (3) Carbon balance: Maintains stronger carbon negativity (-20,709.09 vs. -10,232.06 kg CO₂/ha/year); (4) Market readiness: Compatible with existing flex-fuel infrastructure and E20-E30 blending mandates; and (5) Sustainability alignment: Better supports climate change mitigation goals. H99F production should only be considered for specific niche markets or regulatory requirements that explicitly mandate anhydrous ethanol, as the additional energy input for dehydration significantly diminishes the environmental benefits of the biofuel.

3.2 The estimation of carbon balance

Table 2 shows carbon balance values of -20,709.09 kg CO₂/ha/year for H95F bioethanol production activities and -10,232.06 kg CO₂/ha/year for H99F bioethanol production activities. This means that the total CO₂ emissions produced during bioethanol production activities from nipa sap can all be absorbed by nipa plants, and there is still potential to absorb CO₂ emissions from other nipa plant derivative product production activities, specifically 20,709.09 kg CO₂/ha/year from H95F bioethanol production activities and 10,232.06 kg CO₂/ha/year from H99F bioethanol production activities. It should be noted that the carbon balance estimation did not yet account for the production activities of other nipa plant derivative products.

The production of bioethanol from nipa sap represents a promising renewable energy alternative due to its lower carbon source potential compared to fossil fuels. In its production cycle, nipa plants absorb carbon dioxide through photosynthesis, which is then stored in the sap. The fermentation of nipa sap into bioethanol does produce carbon emissions, but the amount is less than the emissions generated from the extraction and combustion of fossil fuels. Additionally, cultivating nipa plants in coastal areas can serve as an additional carbon sink through their root systems and sediments, making the carbon balance estimation in bioethanol production from nipa sap generally positive.

Factors influencing the carbon balance in nipa sap bioethanol production include sap harvesting methods, the efficiency of sugar-to-ethanol conversion during fermentation, and the energy consumed in distillation and purification processes. Bioethanol production systems that integrate the utilization of nipa biomass waste as an energy source for production can significantly reduce the carbon footprint. Recent studies show that implementing efficient conversion technologies and sustainable cultivation practices can produce bioethanol with greenhouse gas emission reductions of up to 30-90% compared to conventional fossil fuels [20], making it one of the bio-fuel options with high climate change mitigation potential. The potential for climate change mitigation from biofuels varies greatly, where in some scenarios emission levels are comparable to fossil fuels, and in other scenarios, biofuel emissions result in negative emissions.

Table 2. Estimated CO₂-eq emissions from B100 fuel procurement activity.

No.	Parameters	Value	Sources	Description
1	The density of bioethanol from nipah sap can reach (kg/L)	0.84	[12]	Adapted from the density of palm sap.
2	Nipah sap density (kg/L)	0.79	[11]	
3	Nipah sap volume per hectare per year (tons/ha/day)	0.02	[21]	Central Java (100-day production)
		0.46	[21]	East Java (100-day production)
		0.41	[21]	East Kalimantan (100-day production)
		0.27	[21]	South Sulawesi (100-day production)
	Average (tons/ha/day)	0.29		
4	Nipah sap volume per tree per year (L/tree/year)	54.00	[22]	4 harvest cycles per year
		60.00	[22]	4 harvest cycles per year
		1.70	[9]	4 harvest cycles per year
	Average (L/tree/year)	38.57		

No.	Parameters	Value	Sources	Description
5	Number of nipah trees per hectare (trees/ha)	1,972.00	[21]	Kalimantan Region
6	Potential nipah sap production (L/ha/year)	10,000.00	[10]	Lowest for 1,000 nipah palms/ha (100-day harvest period/year)
		50,000.00	[10]	Lowest for 1,000 nipah palms/ha (100-day harvest period/year)
		36,442.95		
		38,026.73	[21]	50% of the total trees per productive hectare produce nipah palm sap.
		Average (L/ha/year)	33,617.42	
7	Bioethanol yield from nipah sap (%) (L/L)	11.74	[23]	Room temperature fermentation using 5% <i>Saccharomyces cerevisiae</i> and 0.6% NPK.
		10.00	[11]	Room temperature fermentation, 10% <i>Saccharomyces cerevisiae</i> , 10% initial sugar content, and added nutrients in the form of urea and NPK.
		24.38	[24]	Fermentation technique using cell immobilization at room temperature.
		18.00	[25]	Fermentation at room temperature for 5 days.
		5.00	[26]	Without fermentation, and passed through a solar collector tube.
		13.00	[27]	Room temperature fermentation.
		7.12	[28]	Fermentation using 10% <i>Saccharomyces cerevisiae</i> , 0.6 g/l urea, and a fermentation time of 36 hours.
		20.47	[29]	Fermentation using 10% <i>Saccharomyces cerevisiae</i> with the addition of 10 ml of Tween 80 and 1 gram of ergosterol over 72 hours, with an initial sugar concentration of 161.81 mg/ml.

No.	Parameters	Value	Sources	Description
		14.00	[29]	Fermentation at room temperature, 10% <i>Saccharomyces Cerevisiae</i> , pH 4.5, for 36 hours, initial sugar concentration of 221.163 mg/ml
		5.50	[30]	7-day fermentation (room temperature) using <i>Saccharomyces Cerevisiae</i>
	Average (%) (L/L)	12.92		
8	Bioethanol per hectare of nipah palm (L/ha)	4,343.87		
9	CO ₂ emissions per L of nipah sap bioethanol (H95F) (Gate to Gate) (kg/L)	0.24	[13]	Hydrous ethanol as pure engine fuel (95% ethanol) (H95F)
10	CO ₂ emissions per L of nipah sap bioethanol (H99F) (Gate-to-Gate) (kg/L)	2.63	[13]	Hydrous ethanol as pure engine fuel (99% ethanol) (H99F)
11	CO ₂ emissions from nipah palm sap bioethanol (H95F) (Gate-to-Gate) per hectare of nipah palm (kg/ha)	1,075.91		
12	CO ₂ emissions from nipah palm sap bioethanol (H99F) (Gate-to-Gate) per hectare of nipah palm (kg/ha)	11,552.94		
13	CO ₂ uptake per hectare of nipah palm (kg/ha)	25,880.00	[1]	
		17,690.00	[2]	
	Average	21,785.00		
14	Nipah palm sap bioethanol carbon balance (H95F) kg CO ₂ per hectare of nipah palm per year (kg CO ₂ /ha/year)	- 20,709.09		Production of other nipah derivative products is not included
15	Nipah palm sap bioethanol carbon balance (H99F) kg CO ₂ per hectare of nipah palm per year (kg CO ₂ /ha/year)	- 10,232.06		Production of other nipah derivative products is not included

It should be noted that the bioethanol yield from nipa sap shows considerable variability across different studies, ranging from 5% to 24.38% (Table 2). This variation is attributed to differences in fermentation conditions, including fermentation temperature, yeast strain and concentration, nutrient supplementation, initial sugar content, fermentation duration, and processing techniques. For this study, we used the average yield of 12.92% to provide a balanced estimate that accounts for this variability. The lowest yields (5-7.12%) typically result from simple fermentation without optimization, while the highest yields (20.47-24.38%) are achieved through advanced techniques such as cell immobilization and

optimized nutrient supplementation. Industrial-scale operations would likely target yields in the mid-range (10-18%) using cost-effective fermentation protocols.

For industrial-scale application, fermentation conditions using 10% *Saccharomyces cerevisiae* with nutrient supplementation (urea and NPK) at room temperature for 36-72 hours represent the most realistic approach [11,28,29]. These conditions achieve yields of 10-14%, which balance productivity with operational costs. While cell immobilization techniques can achieve higher yields (24.38%) [24], the additional infrastructure and maintenance costs may not be economically justified for first-generation commercial facilities. Room temperature fermentation is particularly advantageous for tropical regions like Indonesia, eliminating the need for temperature control systems and reducing energy consumption. Table 3 illustrates the summary of carbon balance for nipa palm bioethanol production systems.

Table 3. Summary of carbon balance for nipa palm bioethanol production systems.

Production System	Bioethanol Production (L/ha/year)	Production Emissions (kg CO ₂ /ha/year)	CO ₂ Sequestration (kg CO ₂ /ha/year)	Net Carbon Balance (kg CO ₂ /ha/year)	Carbon Status	Comparison to Gasoline*
H95F (95% purity)	4,343.87	1,075.91	21,785.00	-20,709.09	Carbon Negative	12.37× lower emissions per liter
H99F (99% purity)	4,343.87	11,552.94	21,785.00	-10,232.06	Carbon Negative	1.11× lower emissions per liter
Gasoline (reference)	-	-	0	+2.91 per liter	Carbon Positive	-

*Gasoline emits 2.91 kg CO₂-eq/L in cradle-to-grave scope [14]

Both H95F and H99F production systems achieve carbon negative status, with the nipa palm plantation sequestering more CO₂ than the entire bioethanol production chain emits. H95F demonstrates superior environmental performance with 95% emission reduction compared to gasoline (12.37:1 ratio) and maintains a stronger carbon sink capacity. The negative values indicate net CO₂ removal from the atmosphere, making nipa bioethanol a climate-positive fuel alternative.

3.3 The sensitivity analysis

To assess the impact of bioethanol yield variability on carbon balance, we conducted sensitivity analysis using three yield scenarios: low (7%), average (12.92%), and high (20%) bioethanol yields (Table 4).

Table 4. Sensitivity analysis of carbon balance under different bioethanol yield scenarios.

Yield Scenario	Yield (%)	Bioethanol Production (L/ha)	H95F Emissions (kg CO ₂ /ha)	H95F Carbon Balance (kg CO ₂ /ha/year)	H99F Emissions (kg CO ₂ /ha)	H99F Carbon Balance (kg CO ₂ /ha/year)
Low	7.00	2,353.22	582.83	-21,202.17	6,264.91	-15,520.09
Average	12.92	4,343.87	1,075.91	-20,709.09	11,552.94	-10,232.06

Yield Scenario	Yield (%)	Bioethanol Production (L/ha)	H95F Emissions (kg CO ₂ /ha)	H95F Carbon Balance (kg CO ₂ /ha/year)	H99F Emissions (kg CO ₂ /ha)	H99F Carbon Balance (kg CO ₂ /ha/year)
High	20.00	6,723.48	1,665.15	-20,119.85	17,894.04	-3,890.96

The sensitivity analysis reveals that even under the most favorable yield conditions (20%), the nipa palm bioethanol system maintains a negative carbon balance (carbon negative), demonstrating the robustness of the system's environmental benefits. The H95F production remains strongly carbon negative across all scenarios (-20,119.85 to -21,202.17 kg CO₂/ha/year), while H99F production, though requiring more energy for purification, still achieves carbon negativity even at maximum yield (-3,890.96 kg CO₂/ha/year). This analysis confirms that the carbon sequestration capacity of nipa palms (21,785 kg CO₂/ha/year) consistently exceeds production emissions regardless of yield variability, underscoring the sustainability of nipa bioethanol as a climate-positive fuel alternative.

4 Conclusion

The findings show that Nipa palms exhibit a substantial CO₂ sequestration capacity, averaging 21,785 kg CO₂/ha/year. The gate-to-gate emissions for producing 95% hydrous ethanol (H95F) and 99% hydrous ethanol (H99F) were calculated to be 1,075.91 kg CO₂/ha and 11,552.94 kg CO₂/ha, respectively. By comparing emissions against sequestration, the study reveals a significant positive carbon balance.

The net balance for H95F production was -20,709.09 kg CO₂/ha/year, and for H99F, it was -10,232.06 kg CO₂/ha/year. Sensitivity analysis across different yield scenarios (7-20%) confirms the robustness of these findings, with the system maintaining carbon negativity under all conditions. This indicates that the bioethanol production system from Nipa sap is not only carbon neutral but carbon negative, as the Nipa palm cultivation absorbs more CO₂ than the entire production process emits.

Analysis of emission sources reveals that distillation processes are the primary contributors to production emissions, accounting for 55.3% of H95F and 91.1% of H99F total emissions. For commercial implementation, H95F is recommended as the primary product due to its superior environmental performance (10.9× lower emissions than H99F), economic efficiency, and compatibility with existing fuel infrastructure. H99F should only be considered for specific applications requiring anhydrous ethanol.

Furthermore, compared to gasoline, which emits approximately 2.91 kg CO₂-eq per liter, Nipa bioethanol presents a much lower carbon footprint, with H95F showing 12.37 times lower emissions per liter. These results underscore the potential of Nipa palm bioethanol as a sustainable and environmentally beneficial fuel source that contributes to mitigating climate change by reducing greenhouse gas concentrations.

Future research should include: (1) direct experimental measurement of nipa bioethanol density at various purity levels to improve calculation precision; (2) investigation of waste biomass utilization for process heat to further reduce emissions; (3) optimization of fermentation protocols for industrial-scale production; and (4) comprehensive cradle-to-grave assessment including land-use change impacts and end-use combustion analysis.

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