Special Issue on APAMS 2026

ARTICLE

Geospatial assessment of non-standard coconut (NSC) for sustainable aviation fuel (SAF) potential in the Philippines

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ABSTRACT

The Philippines, a top global coconut producer, provides a strong basis for quantifying NSC's potential to achieve net-zero emissions in the aviation sector by 2050. This perspective depends on supply chain verification to enable reliable, contextual NSC volume evaluations. To increase accuracy and replicability, ten years of coconut yield records (2015–2024) were integrated. The study used a 20-ha aggregation point to represent typical smallholder farm clusters in major producing regions. Quantified data were processed in ArcGIS Pro to map NSC's spatial distribution in the top three regions: Davao Region, Northern Mindanao, and Zamboanga Peninsula. Hotspot analysis found high NSC density in Davao del Sur, Lanao del Norte, and Zamboanga del Norte, with estimated production of 218,825.58 MT, 174,609.52 MT, and 245,008.32 MT [nut], respectively. A 20-ha aggregation generates 18.9 MT [nut] per harvest season, or 75.9 MT [nut] annually. This feedstock meets ICC (2025) limits of no more than 10 MT per month or 120 MT per year, indicating a low-risk volume that satisfies one traceability standard under CORSIA's sustainability criteria. This serves as an indicative basis for assessing traceability and feedstock aggregation, pending verification of other relevant CORSIA sustainability and certification requirements. Thus, in this scenario, it may produce 3.58 MT annually, making the Davao Region the leading SAF contributor, with an estimated conversion of 31,239.35 MT. In sum, uniform NSC volumes across the top three regions in the Philippines amount to 1.75 MMT [nut], with the most collection points in the Davao Region at 8,726 hubs. This geospatial assessment offers a technical foundation for quantification in future NSC account studies for national SAF adoption, supporting fuel needs and environmental responsibility.

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Email Address: **wcmateo@clsu.edu.ph**
Date received: 22 April 2026
Dates revised: 22 July 2026; 31 August 2026
Date accepted: 13 September 2026
DOI: https://doi.org/10.54645/202619SupRWY-93

INTRODUCTION

The Philippine coconut industry is among the nation's most economically significant and structurally complex agricultural sectors. Coconut products consistently rank among the top ten national agricultural exports, with three coconut-based entries, and the industry supports an estimated 1–3 million Filipinos across farming, processing, trading, and logistics value chains (Costales, 2020). Rather than constituting a single commodity, coconut products comprise a portfolio of interdependent streams: coconut oil generates approximately 70% of export earnings, desiccated coconut contributes around 15%, and copra meal about 4%. The remaining share is distributed among virgin coconut oil, coconut water, coco coir, and oleochemicals such as fatty acids, fatty alcohols, methyl esters, and surfactants, as well as coco methyl ester, which underpins the domestic biodiesel mandate established by the Biofuels Act of 2006 (Philippine Coconut Industry Roadmap 2021–2040).

The coconut industry's multi-product structure means policy or market interventions targeting a single product stream can cascade through the sector. Such interventions may impact farmer incomes, provincial employment, foreign exchange earnings, and domestic diesel fuel costs. The evolution of biofuel policy in the Philippines illustrates the socio-economic sensitivity of this multi-product

KEYWORDS

Aggregation point, CORSIA, Non-standard coconut, Oil-based feedstock, Sustainable aviation fuel

coconut economy (Alonzo, 2016; Encarnacion & Quiros, 2017; Obligado et al., 2017). Empirical analyses reveal a paradox: although coconut farm-gate prices increased, coconut workers' wages declined, and farmer income volatility intensified. This indicates that the benefits of biodiesel policy were not equitably distributed along the value chain (Georges, 2012).

The Biofuels Act of 2006 mandated blending commercial diesel with coconut methyl ester (CME), beginning at 1% and later increasing to 2% (B2). Subsequent research has examined higher biodiesel blends to enhance domestic coconut-oil utilization and support the coconut industry. Currently, this 30% stream is processed into copra, which is then sorted into edible and non-edible grades. Non-edible copra is utilized to produce crude coconut oil (CCO) for non-edible applications, including the domestic biodiesel program. During the January 2025 fieldwork period, the operative biodiesel mandate was B3, following the implementation of the Department of Energy's Department Circular No. 2024-05-0014, effective October 1, 2024. The National Biofuels Board subsequently postponed the increases to B4 and B5, which were originally scheduled for 2025 and 2026, respectively. This policy context establishes a domestic demand for coconut-derived feedstock for CME production. Redirecting non-standard copra toward sustainable aviation fuel (SAF) could therefore reduce the available biodiesel feedstock pool and impact the smallholder-linked oil-mill network, rather than drawing from food-grade coconuts (Piranfar et al., 2019; Tooy et al., 2025). Although non-standard copra does not directly compete with food-grade coconut markets, converting it to SAF may compete with existing road-biofuel, oleochemical, and low-value copra channels that currently utilize this material.

The ASEAN 2050 SAF Outlook Report indicates that the region's estimated bio-feedstock base could theoretically support up to 52.9 million US barrels per year of sustainable aviation fuel (SAF), sufficient to meet projected 2050 jet fuel demand from all regional air operators, contingent upon coordinated policy and feedstock mobilization (GHD, 2026). The report details the SAF development trajectories for Indonesia, Malaysia, the Philippines, Thailand, and Vietnam and identifies regional cooperation and consistent institutional policies as essential enablers (GHD, 2026) . Within this framework, the Philippines is recognized as a strategically important but institutionally underprepared contributor. The Department of Energy acknowledges that the country remains in the early stages of SAF adaptation (Atmowidjojo et al., 2021; Dela Peña, 2025). The report further emphasizes that neither regional cooperation nor consistent institutional policy has been stabilized in the Philippine biodiesel sector (Bhadange & Fitrinitia, 2025; Nguyen & Vuong, 2024; Dela Peña, 2025). Additionally, the literature notes that the Hydroprocessed Esters and Fatty Acids (HEFA) pathway, currently the most cost-effective and commercially mature route for oil-based crops, directly competes with the existing road-transport biofuel market (ICAO, 2024).

In the Philippine coconut sector, the potential diversion of feedstock is a tangible issue: approximately 30% of annual coconut production comprises non-standard coconuts, such as small, sprouted, rotten, and cracked nuts that are rejected by the fresh-market and desiccated-coconut channels (BRIN, 2024; Pambengkas & Jaqin, 2024). Indonesia reports a similar 30% share of non-standard edible coconut production, suggesting this is a structural feature of coconut value chains among ASEAN producers (Tooy et al., 2025). Currently, this 30% stream is processed into copra, which is then sorted into edible and non-edible grades. Non-edible copra is used to produce crude coconut oil for non-edible applications, directly supplying the domestic biodiesel program, which is currently mandated at B2, with a B5 target deferred. This arrangement provides a feedstock floor for the country's CME producers. Redirecting non-standard copra toward SAF would therefore reduce the available biodiesel feedstock pool and impact the smallholder-linked oil mill network, rather than drawing from food-grade coconuts (Tooy et al., 2025). This positions non-standard coconuts (NSC) as a CORSIA-eligible waste stream that both addresses and complicates the food-versus-fuel debate: while it does not compete with food-grade markets, it does compete with the road-biofuel, oleochemical, and low-value-copra channels that currently utilize it (Doliente et al., 2020; Tooy et al., 2025).

Competing demands for coconut oil—including biodiesel, oleochemicals, virgin coconut oil, cosmetics, and more recently SAF—have historically distorted the global coconut oil market and contributed to the long-term decline of copra in several Asian countries. This trend has been influenced by the substitutability of coconut oil with palm kernel oil and other lauric-oil equivalents (Georges, 2012; Prades et al., 2016; Pratama et al., 2024). Carbon footprint assessments indicate that the current CME pathway achieves approximately 77.89% greenhouse gas reduction compared to fossil diesel on a cradle-to-grave basis. This fulfills the Philippines' unconditional NDC contribution of 2.71% under the UNFCCC and establishes the sector as a credible low-carbon fuel producer, independent of the SAF issue (Magadia et al., 2025).

The technological landscape for the utilization of non-standard coconut (NSC) has advanced considerably. Of the four ASTM-certified SAF pathways, HEFA remains the most cost-effective and commercially viable route for oil-based crops, positioning it as the logical technological anchor for the Philippine coconut industry (Goh et al., 2022; Ng et al., 2021; Shehab et al., 2023). Coconut oil possesses a unique advantage due to its medium-chain triglyceride profile (C_8–C_{14}), which closely aligns with the kerosene-range hydrocarbons used in jet fuel. This enables higher selectivity and improved low-temperature performance (Alamsyah et al., 2026). Combustion tests of coconut-derived SAF blended with Jet-A have demonstrated stable operation at blend ratios up to 50%. Specific fuel consumption increased by only approximately 9% compared to neat Jet-A, while combustion efficiency consistently exceeded 90%. These findings provide empirical evidence that coconut oil can serve as a drop-in SAF feedstock (Ogawa et al., 2024).

Overall, expanding SAF initiatives in the Philippines necessitates coordinated regional efforts. The country currently lacks a comprehensive database on non-standard coconuts (Canovas et al., 2024), and the Department of Energy reports that the Philippines remains in the early stages of SAF adaptation. Significant data uncertainty and insufficient evidence regarding the role of non-standard coconuts in the SAF feedstock industry highlight the need for further research and development in this area (IRENA, 2024). Assessing the spatial distribution and potential volume of non-standard coconuts, as well as identifying available post-harvest facilities and collection points, is essential. This study investigates the potential contribution of non-standard coconuts within the Philippine context.

MATERIALS AND METHODS

The assessment of non-standard coconuts feasible in the Philippine context was carried out through both qualitative and quantitative approaches. Researchers used descriptive analysis, field surveys, on-site interviews, and scientific calculations, including literature reviews and outcomes of non-standard coconut experiments. These were integrated into the collection-point sampling scenario to approximate potential NSC volumes. The specified methods were as follows:

Data Collection

On-site visits to the Philippine Coconut Authority National Office and Regions IX, X, and XI were conducted to obtain data on coconut production, biofuels facility points, and coconut farm areas from 2015 to 2024. This 10-year assessment period ensured the credibility of NSC estimates and annual coconut production trend analysis for the top three producing regions: Davao Region, Northern Mindanao, and Zamboanga Peninsula, with an emphasis on the provincial level. The annual provincial coconut production dataset, reported in metric tons (with husk), serves as the basis for estimating non-standard coconut (NSC) availability. Since the analysis was conducted using production values reported directly in metric tons, no conversion from copra-equivalent or nut-count datasets was performed. These data were used to estimate the potential of non-standard coconut on a 30% basis globally and to relate it to local coconut density in the Philippines (Pambengkas & Jaqin, 2024; IRENA, 2024). Collaboration with these offices ensured the data's integrity and credibility and organized the 10-year data for public and research use.

However, a limitation should be taken into account in the data gathered, given climatic disturbances that affect temporal variations in coconut production and other related factors driving fluctuations. The estimated volumes did not account for these factors in the analysis of the results and were based solely on the data provided.

Field Visitation

Researchers visited coconut farm cooperatives, including the *Tagakpan Balingayin Microfarmer Association* (TABAMFA) in Davao City, a cooperative from Misamis Occidental in Northern Mindanao, and the *Bulawan Coconut Farmers Agriculture Cooperative* (BCFAC) in Zamboanga del Sur. Field visits aimed to accurately supervise the coconut farms and related facilities. Farm production was validated through consultations with farmers on daily farm management, operations, production handling, and post-harvest practices. This step was significant for understanding the actual coconut production scenario in the top 3 regions. The visits focused on the potential availability of non-standard coconut and the underutilization of fields, facilities, and collection points where NSC occurs. Interviews with coconut-farming experts helped incorporate their experience into a local perspective for NSC in the Philippines.

Farm Practices On-Site Verification

Farm management and post-harvest practices were both crucial factors in the coconut industry's supply chain in the Philippines. This critical step was investigated on-site simultaneously with the cooperatives identified during the field visit. The coconut supply chain, from harvesting to copra-making and coconut oil extraction, was thoroughly verified within the allotted timeframe to deliberately examine the practices involved, through interviews and surveys using the prepared questionnaire. It includes actual coconut yield per harvest, manual and mechanical operations practiced on the farm, the laborers needed to achieve the per-hectare yield, as well as the input and output volumes of copra from the possible NSC in the field. In this regard, validation of NSC utilization was also technically constrained by seasonality and the off-season dilemma in the Philippines, which hindered the provision of reliable estimates for non-standard coconuts.

Assessment of Non-Standard Coconuts Based on Collection Points

Based on data collection, field visits, and on-site verification of farm practices, the NSC assessment was approximated from a 20-ha aggregate collection point, in accordance with the ICC Coconut Sorting Manual (2025). The 20-hectare unit adopted in this study does not represent the size of an individual coconut farm but rather an aggregation unit intended to reflect a practical feedstock collection area for non-standard coconuts within the supply chain. This approach was selected to estimate the volume of feedstock that could realistically be consolidated from multiple neighboring smallholder farms, which are the predominant production system in the Philippines. The study acknowledges that inter-farm collection logistics, transportation distances, and cooperative organization may influence the operational feasibility of such aggregation and that these factors were not explicitly modeled in this assessment.

Based on actual harvest yields and annual considerations, NSC volume was estimated using a literature review of studies by Tooy et al. (2025) and Kothari et al. (2024) on the chemical investigation of NSC for bioenergy production. With a 10-year data-collection period, a global-scale 30% feasibility rate for NSC, and farm-practice quantitative results, technically estimated potential volumes for NSC were calculated. The estimation was calculated in Microsoft Excel and incorporated into the spatial distribution of the Philippines' top 3 coconut-producing regions in ArcGIS Pro.

In line with the estimation, the ICC (2025) threshold of no more than 10 MT per month or 120 MT per year was cited to demonstrate compliance with traceability requirements for non-standard coconut feedstocks rather than as a parameter used in the spatial estimation model. Accordingly, the threshold was not operationalized to classify or filter collection points because the study focused on estimating the theoretical availability of feedstock at the provincial level rather than evaluating individual collection centers.

Sensitivity Analysis of Estimated NSC Potential

Given that the 30% NSC rejection rate is a scenario-based assumption and that Philippine-specific measurements of annual NSC generation are limited, a one-way sensitivity analysis was conducted to assess the impact of rejection-rate variability on estimated NSC availability and SAF potential. Five scenarios were evaluated: 20%, 25%, 30%, 35%, and 40%, with 30% serving as the base-case assumption.

In each scenario, only the rejection rate was varied, while all other parameters—including coconut production data, material conversion factors, processing yields, and HEFA conversion efficiency—remained constant. The resulting NSC quantities and corresponding SAF potentials were recalculated to determine the effect of rejection-rate variability on overall feedstock potential. These SAF estimates were then compared with the projected national aviation fuel demand of 2.1 million MT.

This analysis was designed to characterize uncertainty in the assumed rejection rate, rather than to represent statistically observed annual variation. The resulting range provides a scenario-based estimate of potential NSC availability and SAF production, and underscores the need for Philippine-specific, multi-season field measurements to establish more representative rejection rates in future assessments.

Selection of Conversion Pathways

Non-standard coconut (NSC) can be utilized through various thermochemical and biochemical conversion pathways for sustainable aviation fuel (SAF) production. GHD (2026) identifies Fischer–Tropsch (FT), hydrothermal liquefaction (HTL), and hydroprocessed esters and fatty acids (HEFA) as potential routes for converting biomass resources into aviation fuel. FT converts gasified biomass-derived syngas into synthetic hydrocarbons, while HTL processes wet biomass into biocrude that requires subsequent upgrading to produce aviation-range hydrocarbons. In this study, the HEFA pathway was selected because the feedstock

under investigation is non-standard coconut processed into coconut oil. As a lipid-rich feedstock, coconut oil is directly compatible with the established HEFA conversion route. In contrast, FT and HTL generally require additional thermochemical conversion, intermediate production, and upgrading steps. Under CORSIA, coconut oil is classified within the oil feedstock category, which is specifically designated for the HEFA pathway to convert feedstock to SAF. Therefore, the HEFA pathway more directly and consistently represents the NSC-to-SAF chain evaluated in this study (ICAO, 2024). FT and HTL are recognized as alternative pathways that merit further assessment, particularly for other coconut residues and non-lipid fractions. Excluding FT and HTL in this assessment does not suggest that HEFA is the only technically feasible pathway for coconut-derived SAF; rather, it reflects the feedstock-specific scope and system boundary adopted in the present analysis (GHD, 2026).

Quantification of Potential Collection Points

Potential collection points for non-standard coconuts (NSC) were estimated using sample-based production stream data derived from an aggregated assessment of a 20-hectare coconut farm. The mean NSC output observed during validation was used to estimate the coconut farm population in each region and to approximate the total NSC supply, applying a 30% global scale assumption.

The number of potential collection points was calculated by dividing the estimated regional NSC supply by the minimum viable aggregation volume per collection point, while considering farm clustering and logistical feasibility. This method enabled the estimation of the required number of collection points in the top three (3) regions.

Spatial Distribution of Non-Standard Coconut Volumes

The estimated NSC volumes were used to determine the spatial distribution across the top 3 coconut-producing regions: Davao Region, Northern Mindanao, and Zamboanga Peninsula. This involves presenting the provincial-level perspective on the potential of NSC volumes to contribute to the Sustainable Aviation Fuels (SAF) initiative in the Philippines. The mapping was generated in ArcGIS Pro using hotspot analysis to visualize the dense occurrence of NSC for SAF. Quantified data from the aggregation-point sampling basis were used to present the NSC volume potential in the top three (3) provinces producing coconut. This includes range volume, indicating the low and high occurrences of NSC in the land area provided for coconut, which will later be used for further studies on co-processing SAF in the Philippines.

RESULTS AND DISCUSSION

With robust energy demand and the challenge of optimizing feedstocks to address rising carbon emissions, particularly in aviation fuel, Non-Standard Coconut (NSC) has been eyed as a valuable by-product that could be enlisted by CORSIA for conversion into Sustainable Aviation Fuel. Consequently, the scenario analyzed in the volume assessment, aligned with sorting management points, was based on the regional level of farm practices, integrated with standards and actual verification of the current state of coconut farmland in the Philippines. The assumptions and limitations rely on the specific boundaries theoretically defined in the literature, on-site visitation, and face-to-face verification in the top 3 regions (Davao Region, Northern Mindanao, and Zamboanga Peninsula), significantly contributing to the volume of coconut production in reliance as well as to the potential scenario of Non-Standard Coconut (NSC) in the areas.

Farm Practices within the 20-ha Aggregated Point as a Potential Integrated Sorting for NSC

A. Davao Region

The trend in coconut production has led to a significant increase, from roughly 14.93 MMT in 2022 to levels seen in previous years (Balita, 2023; FAO, 2023). However, it has recently decreased to 14.89 MMT in 2023 (PSA, 2025). Emerging as a major contributor to this volume, the Davao Region contributed 1.98 MMT in 2023, corresponding to Northern Mindanao and the Zamboanga Peninsula.

In this regard, the area has been visited, and coordination has been closely conducted with personnel from the Philippine Coconut Authority (PCA) and the Tagakpan Balingayin Microfarmer Association (TABAMFA). This cooperative operates on a 20-hectare land with a copra-making facility that is continuously in operation. Harvesting typically occurs every three months, with an expected production of 2,100 nuts from 100 trees planted in a spacing of 10 by 10 meters, in accordance with the Code of Good Agricultural Practices (GAP) for Coconuts (PNS 238:2018).

Coconut farming begins with harvesting, which is typically done with a *sungkit,* a traditional tool that eliminates the need to scale the tree (see Figure 1). This technique allows a harvester to use a long pole made of bamboo or lightweight wood, equipped with a sharp, sickle-like blade. Upon being cut from the tree, the bunches typically fall to the ground; however, in many instances, they are cushioned by leaves, soil mounds, or nets to reduce cracking. The harvested coconuts are then gathered in one area for collection by a tractor, which has the capacity to transport 500 kg of nuts/ (approximately 250 whole nuts) per operational cycle, based on the average standard nut size of 1-2 kg (Gunarathne et al., 2018).

Dehusking and splitting of coconuts are done manually before the coconut meat is dried. The drying process employs a smoke kiln capable of processing 6,000 coconuts in 8 hours, using two drums and coconut husk as the heating medium. After drying, the coconuts are deshelled to separate the meat; 4.5 kg of nuts yield 1 kg of copra.

These practices are primarily manual and have been traditionally integrated to meet the region's ongoing demand for food and fuel. The dried coconut meat, which is yellowish, is commonly used in the fuel industry, including biodiesel production in the Philippines. Over the past 30 years, these traditional methods have been optimized and continuously play a significant role in the Philippines' biodiesel production.

B. Northern Mindanao

Following Davao Region's contribution, Northern Mindanao ranks second among major contributors to the overall volume of coconut production in the Philippines, with 1.88 MMT in 2023 (PSA, 2025). Its farm area comprises 80% tall varieties and 10-20% dwarf varieties.

The farming practices resemble those of the Davao Region, with manual dehusking, splitting, and deshelling; however, they differ in harvesting and collection, with either climbing or *sungkit used depending* on cost-effectiveness (see Figure 1). For

hauling to processing facilities, animal draft is used instead of tractors. Meanwhile, drying can be achieved mechanically using a copra dryer provided by the PCA to cooperatives. Nonetheless, many small-scale farmers still prefer traditional kiln operation over the industrial drying methods. As a result, whole nuts are often transported to commercial facilities without being processed into copra for biofuels, thereby creating a significant imbalance between the food and fuel markets.

C. Zamboanga Peninsula

Significantly, the Zamboanga Peninsula accounts for the upstream of coconut production, with 1.84 MMT in 2023, notably the largest area of 453,228.88 hectares for coconut plantations. With farmers' adherence to Good Agricultural Practice (GAP), small-scale farmers rely on their methodological practices in manual operations, from harvesting to copra making, particularly the smoke-kiln drying process. They rely on animal draft to gather coconuts from *sungkit*, then transport them to a drying facility located on the farmland, typically 1-3 km away, depending on the location of the gathered nuts. Pre-processing before extraction, such as dehusking, splitting, drying, and deshelling, is performed manually in sync. These operations are labor-intensive but environmentally inclusive, using biomass such as coconut husk and shell for energy generation (see Figure 1).

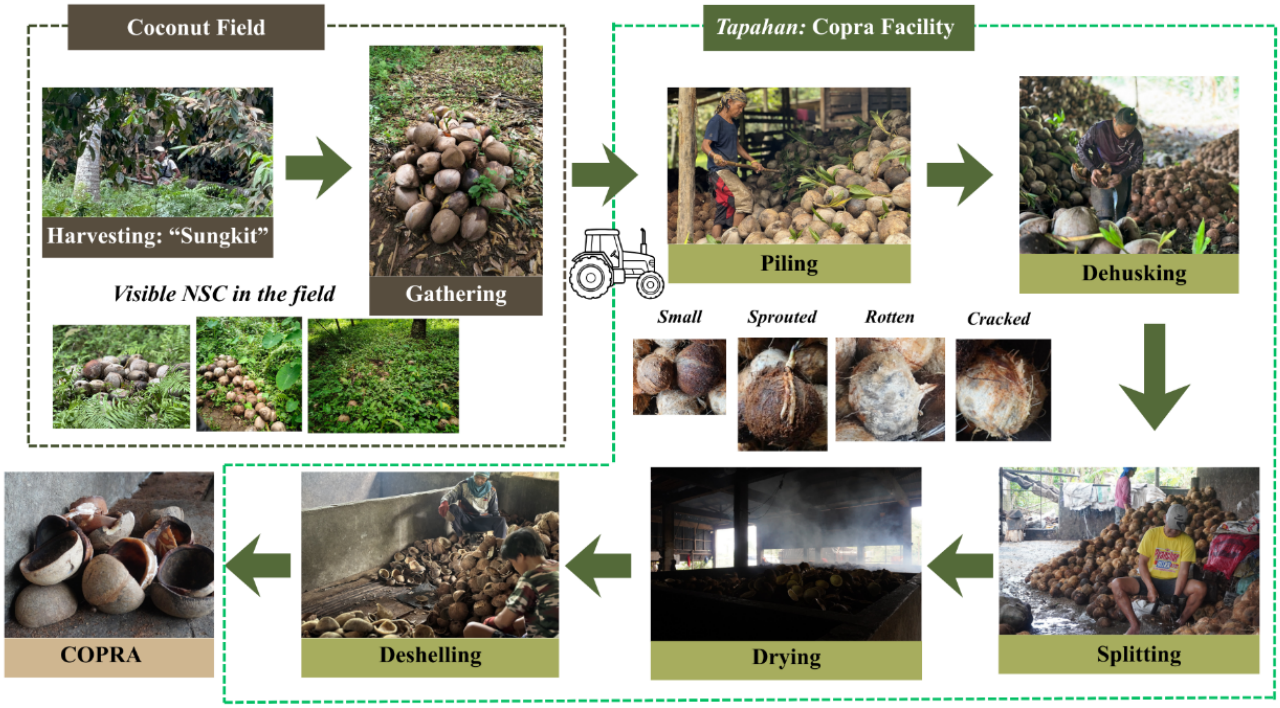


Figure 1: Coconut supply chain validated, identifying NSC availability through field visitation (Regions IX, X, and XI)

Non-Standard Coconut (NSC) Availability Potential Based on the Scenario of Farm Practices in the Philippines

NSC availability, as shown in the supply chain (see Figure 1), begins in the field. Following harvest, if coconuts remain unprocessed and are stored for a month, approximately 2 out of 5 nuts (40% of the sprouting potential) are observed to sprout in the field. Such delays introduce economic challenges, as the supply and demand for copra fluctuate seasonally. Demand peaks between September and February, then declines during the off-season, resulting in market values ranging from 60 to 13 pesos per kilogram [copra]. This price fluctuation has had a significant impact on the potential streams of NSC availability and, at the same time, on the marketability of SAF over a long period, which also corresponds to crucial policy implementations and seasonal demand for copra in different industrial utilizations. As observed in farm practice, this critical scenario will significantly impact policy integration across all systems in the coconut industry of the Philippines, with respect to adherence to global mandates and sustainability standards as its baseline for modeling all areas of potential NSC streams in the supply chain, more importantly, the traceability of the said feedstock.

Small coconuts compete with dwarf varieties, which typically weigh approximately 0.8 kg, according to Tooy et al. (2025). Despite their physical limitations, these small coconuts retain value for producers. Additionally, rotten coconuts or those older than 12 months, weighing around 0.36 kg according to Kothari et al. (2024), pose significant challenges. Furthermore, cracked coconuts occur during post-harvest distribution and management. The value of these coconuts varies considerably, underscoring the need for value-added strategies to maximize production yields, particularly in the face of unavoidable climatic events such as typhoons. This scenario suggests a system supported by systematic accounting and grading selection, as recommended by ICAO (2024), and in compliance with the ICC (2025) Sorting Manual requirements for SAF application.

In line with this, NSC potential can be estimated both in the field and at the pre-processing facility, known as *tapahan,* which processes even classified NSC into copra, given the economic side. However, the scope of the estimation was based entirely on the copra facility scheme, in which all categories were observed, as shown in Figure 1 (*tapahan* boundary flow). In this system flow, NSC can be approximated in the aggregated system by following

the sorting manual procedure to quantify potential NSC volumes, while observing all four categories in the scheme.

These considerations underscore the need for coconut farmers to integrate the NSC with industry standards across food-grade coconuts and by-product markets. Such integration supports the development of markets that are less dependent on seasonal or economic fluctuations and instead focus on balancing fuel requirements with environmental responsibility. In response to growing concerns about climate action and the balance between food security and fuel demand, the NSC has adopted oil-based feedstocks for Sustainable Aviation Fuel (SAF). This initiative could significantly improve post-harvest supply chain development in the Philippines, thereby addressing the underutilization of coconuts. Formalizing the NSC supply chain may provide smallholder farmers with an additional revenue stream from underutilized materials while creating employment opportunities in collection, transportation, and processing. Integrating farmer cooperatives, transparent pricing mechanisms, and government-supported extension services can promote equitable participation and benefit-sharing throughout the supply chain.

Non-Standard Coconut Physical Characterization in *Tapahan* (Copra Making Facility)

During field visits to *Tapahan (copra-making* facility), it was observed that the piled-up dehusked nuts (see Appendix Figure 3) were categorized as non-standard coconuts, as shown in Figure 5, including small-sized, rotten, cracked, and sprouted coconuts. A small coconut (Figure 2a) shows reduced nut diameter and mass compared with standard mature coconuts, which are shown beside it for comparison. Specifically, diameter and weight can both be used as criteria, with a weighing scale and a ring gauge to measure diameter. Specifically, it should pass the standard measures of less than 700 grams in mass and less than 9.5 cm in diameter (Annex 1 - Type A), according to ICC (2025). Rotten (Figure 2c) exhibits a molded texture on its outer shell and surface discoloration, indicating microbial contamination of the coconuts. Furthermore, the shell fracture during piling indicated a cracked classification (Figure 2d), as evidenced by its physical damage. Ultimately, sprouted (Figure 2b) shows observable germination, revealing root system growth. These characterizations were also defined and validated in accordance with ICAO-CORSIA (2024) and Kothari et al. (2024).aax

Significantly, these samples indicated that the facility lacks a standardized approach to sorting mature coconuts for further processing, regardless of whether they exhibit visible deformities that deviate from market standards for high-quality copra. Then, NSCs are often blended with standard coconuts due to limited sorting capabilities and economic pressure to maximize volume rather than prioritize quality. Nevertheless, the occurrence of these non-standard coconuts in the value chain highlights SAF's potential, which was added to the ICAO-CORSIA list of oil-based feedstocks in March 2024 and, in the Philippine context, underscores its viability. Hence, this suggests the Philippines' positive contribution to the global initiative to decarbonize aviation.

However, to provide quality measures for NSC classification in compliance with ICAO-CORSIA, sorting facilities within a single point of origin, specifically a single collection point, should be established and follow the quality measures outlined in the Coconut Sorting Manual (ICC, 2025). Whereas the successful integration of NSCs into the SAF supply chain requires a robust traceability and quality assurance system. Given the risk of feedstock mixing between non-standard and market-grade coconuts, implementing standardized inspection protocols, batch-level traceability, digital inventory management, and periodic third-party audits would strengthen compliance with CORSIA sustainability requirements. These mechanisms enhance transparency throughout the supply chain by ensuring that only eligible feedstocks are processed and by maintaining a verifiable chain of custody from collection to conversion.

Furthermore, effective implementation depends on institutional support through regular monitoring, capacity-building initiatives for farmers and collectors, and regulatory oversight by agencies such as the Philippine Coconut Authority (PCA). Integrating these governance mechanisms into the proposed collection network would improve feedstock integrity, increase stakeholder confidence, and facilitate future sustainability certification. Consequently, establishing a transparent and accountable supply chain not only minimizes the risk of feedstock contamination but also enhances the practical feasibility and long-term credibility of NSC-derived SAF production in the Philippines.



Figure 2: Representative samples of non-standard coconuts (NSC) identified in the *tapahan* (copra-making facility): showing (**a**) small, (**b**) sprouted, (**c**) rotten, and (**d**) cracked physical deformities, respectively.

Estimated Volume of NSC from the 20-ha Aggregation (Collection Point) Scenario of Coconut Farmland with Copra Making Facility (*Tapahan)*

The Sankey diagram in Figure 3 illustrates the biomass flow and product distribution for non-standard coconuts (NSC) collected from a 20-hectare aggregation of coconut farmland, which serves as an integrated collection point for rejected coconuts. The estimation of NSC volumes is based on the 30% coconut rejection rate reported by IRENA (2024) for the Philippines. Under the ICC (2025) framework, the 20-hectare aggregation qualifies as a potential single collection point, ensuring compliance with one of the traceability criteria for Sustainable Aviation Fuel (SAF) feedstocks, particularly for non-standard coconut utilization.

Each quarterly harvest yields approximately 18.90 MT of NSC, which is further fractionated into coconut components through standard coconut processing. From this volume, the biomass is distributed into 4.91 MT of coconut meat, 8.51 MT of husk, 1.70

MT of coconut water, and 3.78 MT of shell. During copra production, 2.14 MT of moisture is removed from the meat, resulting in 2.77 MT of dried copra. This dried copra is processed into 1.73 MT of crude coconut oil (CCO), which serves as the principal feedstock for Sustainable Aviation Fuel production through the Hydroprocessed Esters and Fatty Acids (HEFA) pathway (ICAO, 2024). In addition, 0.64 MT of copra cake is produced as a co-product, while 0.40 MT is accounted for as processing losses. Based on this oil output, the quarterly NSC supply demonstrates a SAF production potential of approximately 0.89 MT.

Other coconut components are also effectively utilized within the system. The 8.51 MT of husk is converted into 3.40 MT for kiln-drying applications and 5.11 MT for geonets and other fiber-based materials, thereby supporting value-added coconut fiber industries. The 3.78 MT of coconut shells are fully processed into charcoal, while 1.70 MT of coconut water remains largely underutilized and presents an opportunity for further value-added processing. This distribution demonstrates a resource-efficient, low-waste utilization pathway, in which most biomass fractions are directed toward productive uses.

When the system is projected annually, the NSC supply increases proportionally to 75.60 MT of non-standard coconuts. Applying the same processing structure, this volume produces 19.66 MT of coconut meat, 34.02 MT of husk, 6.80 MT of coconut water, and 15.12 MT of shell. From the meat fraction, 8.57 MT of moisture is removed, yielding 11.08 MT of dried copra, which is subsequently converted into 6.93 MT of crude coconut oil. This oil volume corresponds to an estimated 3.58 MT SAF potential annually, while 3.33 MT of copra cake and 0.81 MT of processing losses are generated as by-products.

Similarly, the annual husk output of 34.02 MT supports 13.61 MT of kiln-dried biomass and 20.41 MT of geonet and fiber products, while the 15.12 MT of coconut shells can be fully processed into charcoal. The 6.80 MT of coconut water continues to represent an underutilized stream that could be explored for additional product development.

Overall, the Sankey analysis demonstrates that all coconut components contribute to productive biomass utilization, while dried copra remains the only fraction directly contributing to coconut oil production for SAF feedstock. The scaling from quarterly to annual estimates confirms the consistent availability of NSC-derived biomass for renewable fuel production while maintaining efficient co-product utilization.

These results highlight that non-standard coconuts are a viable feedstock for sustainable aviation fuel without disrupting food-grade coconut markets. Furthermore, the use of NSC for SAF production does not preclude the recovery and use of valuable co-products, such as husks, shells, coconut water, and copra cake. In this study, the proposed SAF pathway assumes that these co-products remain available for their conventional uses, including husks and shells as biomass fuel for copra drying and other value-added applications, consistent with an integrated biorefinery approach. This co-product allocation remains consistent by transforming rejected coconuts into fuel from the coconut meat itself, without disrupting the main utilization of value-added co-products in industrial operations, thereby supporting circular bioeconomy principles, improving resource recovery, and diversifying income opportunities for coconut-producing regions in the Philippines (Tooy et al., 2025).

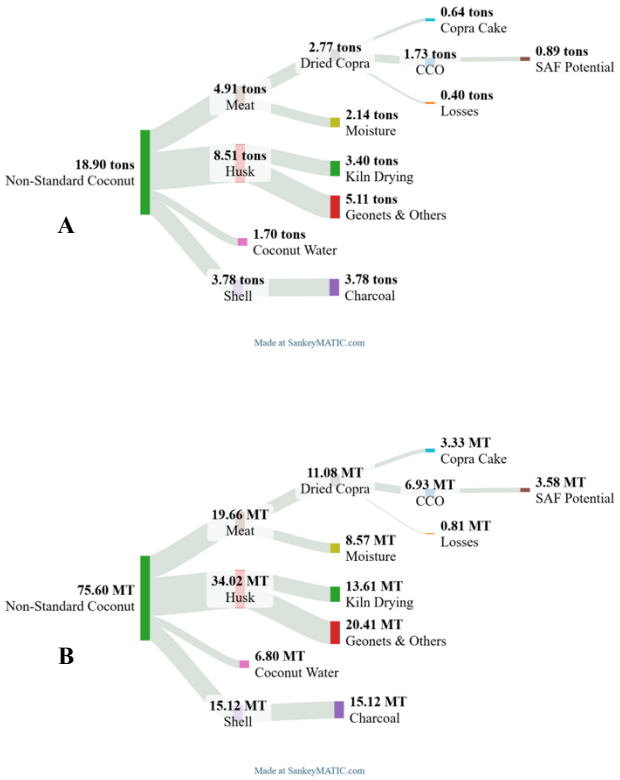
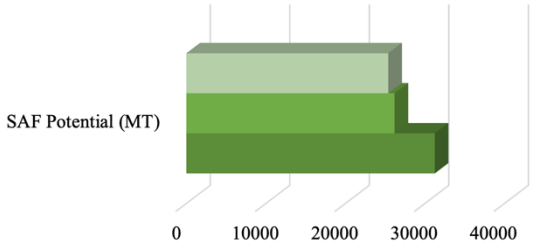


Figure 3: Projected NSC volume for a 20-ha coconut farmland [**A**: Quarterly Collection & **B**: Annually Collection]

Assumptions and Limitationsa

The data in Figure 3 are only projections and theoretical calculations based on a scenario of 30% non-standard coconut in the Philippine setting (IRENA, 2024). Hence, most are based on secondary data, derived from the literature to understand the trend of non-standard coconut, and scaled up to the national level.

SAF Potential from the Top 3 Regions NSC Volumes Estimated



	SAF Potential (MT)
Zamboanga Peninsula	25390.15
Northern Mindanao	26182.6
Davao Region	31239.35

Figure 4: Estimated SAF potential based on NSC volumes from the top three regions in MT.

Figure 4 presents the estimated SAF potential derived from NSC volumes in the three major coconut-producing regions in Mindanao. The Davao Region has the highest estimated SAF potential at 31,239.35 MT, followed by Northern Mindanao at 26,182.60 MT and the Zamboanga Peninsula at 25,390.15 MT. Collectively, these regions provide an estimated 82,812.10 MT of potential SAF. Compared with the projected 2.1 million metric tons of national aviation fuel demand in the Philippines by 2024 (DOE, 2024), the SAF potential from these three regions would account for approximately 3.94% of the total demand. Furthermore, this result is broadly consistent with the national assessment reported by

IRENA's findings, which estimated approximately 0.6 million metric tons (Mt) of annual SAF potential from Philippine non-standard coconuts (NSCs). Although this contribution is insufficient to fully replace conventional aviation fuel, it demonstrates the strategic potential of NSCs as a sustainable, non-food feedstock that can complement other biomass resources within a diversified national SAF portfolio. As an agricultural by-product, NSCs offer an opportunity to expand renewable fuel production without competing with food-grade coconut markets, thereby supporting circular bioeconomy principles and resource efficiency. Consequently, the present study covers only three major coconut-producing regions; the estimated production represents a substantial proportion of the national potential, indicating that the spatial resource assessment aligns with broader national projections.

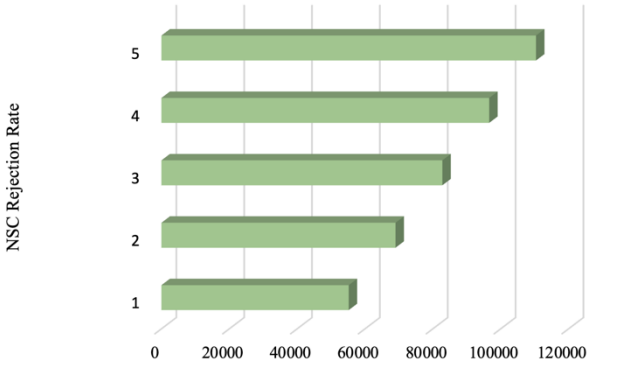
The spatial distribution of SAF potential further provides a practical basis for national policy and investment planning by identifying regions with the greatest capacity to support feedstock aggregation and future SAF development. The higher production potential observed in the Davao Region, Northern Mindanao, and the Zamboanga Peninsula highlights these areas as priority locations for pilot-scale SAF projects, collection and processing infrastructure, and logistics networks that can strengthen feedstock mobilization. These findings can support government agencies in developing biomass resource inventories, regional investment priorities, and incentive mechanisms that encourage private sector participation while promoting compliance with sustainability requirements such as CORSIA. Consequently, NSC-derived SAF should be viewed as one component of a broader multi-feedstock strategy that integrates other locally available waste-derived biomass resources, thereby contributing to the Philippines' long-term goals of aviation decarbonization, renewable energy diversification, and greenhouse gas emission reduction.

Furthermore, these results demonstrate that the scalability of NSC-based SAF production is significantly influenced by feedstock logistics and aggregation infrastructure. Given the geographic dispersion of coconut farms, the development of multiple localized hubs is essential for efficiently collecting, processing, and transporting NSC for conversion into SAF. Therefore, regional hub systems, particularly in high-potential areas such as the Davao Region, could play a critical role in strengthening the supply chain for coconut-based SAF production and supporting the broader transition toward more sustainable aviation fuels in the Philippines.

Sensitivity Analysis of the NSC Rejection Rate

NSC availability was estimated using a 30% rejection rate, as adopted from previous literature (IRENA, 2024). Since this parameter is a scenario-based estimate rather than a Philippine-specific, year-resolved observation, its potential variability was assessed through sensitivity analysis. We evaluated NSC rejection rates of 20%, 25%, 30%, 35%, and 40%, while maintaining consistent coconut production data, conversion factors, and spatial allocation procedures as in the base case.

The resulting SAF potentials were 55,208.07, 69,010.08, 82,812.10, 96,614.12, and 110,416.13 MT, respectively (see Figure 5). The 30% scenario was retained as the base case, corresponding to approximately 3.94% of the projected 2.1 million MT national aviation fuel demand. These results show that SAF potential is directly proportional to the assumed NSC rejection rate and highlight the uncertainty of applying a uniform rejection factor across a 10-year production dataset.

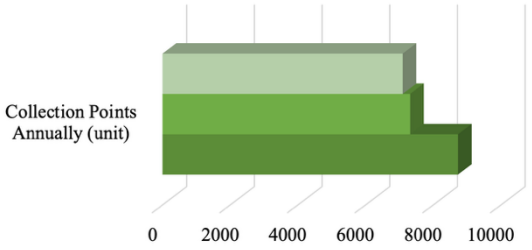


	1	2	3	4	5
NSC rejection rate	20%	25%	30%	35%	40%
SAF potential (MT)	55,208.07	69,010.08	82,812.10	96,614.12	110,416.13

Figure 5: Sensitivity Analysis of SAF Potential to NSC Rejection Rate

The sensitivity analysis indicates that climatic variability, seasonal production, and differences in farm and post-harvest conditions can substantially affect the quantity of NSC available for SAF production. However, the spatial concentration of potential feedstock remains unchanged, as the sensitivity analysis alters only the magnitude and not the underlying distribution of coconut production. The 30% estimate should therefore be interpreted as a planning scenario rather than a fixed annual supply. Future assessments should incorporate multi-season field measurements to develop region-specific and time-varying NSC rejection factors.

Potential Collection Points Needed for the NSC Volumes Estimated in the Top 3 Regions



	Collection Points Annually (unit)
Zamboanga Peninsula	7092
Northern Mindanao	7313
Davao Region	8726

Figure 6: Quantified potential collection points based on estimated NSC volumes in the Top 3 regions

The quantified number of potential NSC collection points annually in Figure 6 provides figurative support for SAF production from coconut biomass using the 20-hectare aggregation model. The results indicate that the Davao Region would require the most collection hubs at 8,726, followed by Northern Mindanao with 7,313 and the Zamboanga Peninsula with 7,092. These values reflect the scale of coconut-farming areas and the availability of non-standard coconuts that can be aggregated and used for sustainable aviation fuel (SAF) production. These hubs represent theoretical aggregation points rather than proposed new infrastructure, given the existence of *tapahan* (copra processing facilities), cooperatives, trading centers, and PCA-supported facilities. Potentially, these can be used as collection hubs to minimize the economic barriers to scalability.

These results underscore the necessity of a decentralized feedstock aggregation system. Given that coconut farms in the Philippines are generally small and widely distributed, establishing multiple localized collection hubs is essential for efficient NSC biomass

collection. Under the 20-hectare aggregation model, each hub serves as a primary consolidation point for rejected coconuts from nearby farms, facilitating collection, sorting, and preparation for downstream processes such as copra production, oil extraction, and SAF conversion. The greater number of required hubs in the Davao Region aligns with its higher SAF production potential, demonstrating that regions with larger coconut outputs require more robust collection infrastructure.

From a national perspective, these findings highlight that feedstock logistics and aggregation capacity are critical determinants of SAF scalability. Even though the combined SAF potential from the top three regions contributes only a small portion of the 2.1 MMT of aviation fuel demand of the Philippines, the establishment of thousands of collection hubs demonstrates the extensive supply-chain network required to mobilize agricultural residues for energy production. Therefore, developing efficient regional aggregation systems, farmer participation mechanisms, and transport linkages will be essential for enabling the transition from dispersed coconut biomass resources to a reliable feedstock supply for SAF production in the country.

Economic and Supply Chain Integration

Establishing an NSC-SAF supply chain necessitates coordinated participation among coconut farmers, farmer organizations, collection hubs, processors, SAF producers, and government institutions. Transparent NSC pricing may be achieved through a published reference price or a pricing formula that incorporates quantity, quality, moisture content, and transportation requirements. Standardized weighing, delivery receipts, and traceability records improve transaction transparency and provide a verifiable basis for farmer payments.

Farmer cooperatives and collection hubs function as intermediaries for NSC aggregation, quality classification, record-keeping, and transportation to processors. Government extension services support this system by providing training on NSC identification, segregation, post-harvest handling, quality management, traceability, and market participation. These mechanisms reduce transaction costs and information asymmetry, thereby strengthening smallholder farmers' capacity to participate in the emerging NSC market.

In the proposed supply chain, NSC is segregated at the farm level, aggregated and documented at collection hubs, processed into coconut oil, and subsequently converted to SAF via the HEFA pathway. Long-term supply agreements among cooperatives, processors, and SAF producers enhance feedstock security, while periodic price and supply reviews accommodate changes in production, transport costs, and market conditions. Procurement should be restricted to genuinely non-standard or rejected coconuts to minimize diversion of marketable coconuts from existing food and industrial uses.

Implications for Existing Coconut Product Value Chains and Smallholder Livelihoods

The estimated non-standard copra (NSC) resource should be considered within the existing multi-product coconut value chain, rather than as an entirely unallocated feedstock. While NSCs are typically excluded from food-grade and higher-value channels, they are utilized in lower-value processing streams, particularly for copra production and the extraction of non-edible crude coconut oil (CCO). This CCO supplies the coconut methyl ester (CME) industry for road biodiesel, and other coconut-oil fractions and low-value copra are used in oleochemical and other non-food applications. Therefore, diverting NSC-derived copra or oil toward sustainable aviation fuel (SAF) production could reduce feedstock availability for these established downstream users. This issue is especially pertinent under the B3 biodiesel mandate in effect during the January 2025 fieldwork, as domestic CME producers continue to require coconut-derived feedstock. Piranfar et al. (2019) demonstrated that increased biodiesel blending can raise domestic coconut-oil utilization and influence the economic conditions of the Philippine coconut sector, illustrating how fuel policy changes can affect coconut-oil markets. Similarly, Magadia et al. (2025) highlighted the established role of Philippine coconut-derived biodiesel in achieving significant greenhouse-gas reductions, reinforcing the importance of coconut oil in the country's low-carbon transport-fuel system.

The potential diversion of NSCs to SAF production may have implications that extend beyond feedstock availability. Increased demand for coconut oil can influence both coconut oil and copra prices, while fluctuations in international coconut oil markets and competing demand from biodiesel, oleochemicals, virgin coconut oil, and other applications can affect farmgate price conditions. These market dynamics are particularly significant for smallholder coconut farmers whose income depends on selling copra and other coconut products. Although this study identifies NSCs as non-standard and potentially suitable for CORSIA-eligible SAF production, allocating them to SAF should not be assumed to have no socioeconomic opportunity cost. The central policy question is whether NSCs can be mobilized as an additional feedstock while ensuring sufficient supply for existing CME, copra, and other non-food value chains, and avoiding negative impacts on farmgate prices and smallholder livelihoods. The spatial estimates in this study can identify regions with substantial NSC availability, but they do not independently confirm that the estimated quantities are fully available for SAF after accounting for existing uses.

CORSIA Compliance and Sustainability Criteria

In addition to sorting and traceability, NSC-derived sustainable aviation fuel (SAF) must comply with the sustainability criteria established for CORSIA-eligible fuels. Beyond demonstrating feedstock origin and traceability, an NSC-derived SAF pathway must show the required life-cycle greenhouse gas (GHG) emissions reduction compared to the relevant CORSIA aviation-fuel baseline of 89 gCO_2e/MJ, with a goal of 10% minimum reduction. However, for NSC-based SAF, the GHG emission threshold of 26.9 g CO_2e/MJ must be met and applies when hydrogen inputs are not derived from coal. If coal-based hydrogen is used, apply a correction factor of 5.17 g CO_2e/MJ, resulting in a total of 32.07 g CO_2e/MJ, which may exceed the SAF's acceptable sustainability limits (ICAO, 2024). The life-cycle assessment should include emissions from feedstock collection, processing, transportation, SAF conversion, and all other relevant life-cycle stages, including land-use-change emissions where applicable. Previous studies on Philippine coconut-derived biodiesel have indicated significant potential for life-cycle GHG reductions (Landoy et al., 2022; Magadia et al., 2025). For instance, Magadia et al. (2025) reported a 77.89% GHG reduction for the Philippine coconut methyl ester (CME) pathway. Previous life-cycle assessments of Philippine coconut biodiesel provide evidence of the climate-mitigation potential of coconut-derived fuels. Landoy et al. (2022) estimated GHG-reduction potentials of 1.06%, 2.65%, 5.31%, and 10.61% at biodiesel blending levels of 2%, 5%, 10%, and 20%, respectively. However, this finding does not constitute direct evidence of CORSIA compliance for NSC-derived SAF, as the CME and NSC-to-SAF pathways involve different conversion processes, system boundaries, and sustainability-accounting requirements. Rather, the CME results provide supporting evidence of the environmental potential of coconut-derived fuels, but NSC-derived SAF requires a distinct, pathway-specific lifecycle assessment.

For the Philippine NSC pathway, the traceability system outlined in this study provides a foundation for future CORSIA certification

by maintaining detailed records of feedstock origin, quantities collected, sorting and aggregation activities, transportation, processing, and the transfer of material into the SAF production chain. These records should be integrated with pathway-specific GHG calculations and supporting land-use documentation. The resulting sustainability claims must then undergo independent verification and certification under a CORSIA-approved sustainability certification scheme. Consequently, this study establishes the spatial resource and traceability framework for NSC utilization but does not assert that the estimated NSC resource or the resulting SAF is currently CORSIA-certified.

Comparative Assessment of SAF Potential Estimates

The estimated sustainable aviation fuel (SAF) potential from the three assessed regions is 82,812 MT yr^{-1}, representing approximately 39.6% of the national non-subsidized copra (NSC) resource. Extrapolating this regional result to the national scale yields an indicative SAF potential of approximately 0.21 MT yr^{-1}. This value is lower than the 0.27 MT yr^{-1} SAF potential estimated by IRENA (2024) for NSC-derived oil via the hydroprocessed esters and fatty acids (HEFA) pathway, corresponding to approximately 78% of the IRENA estimate. IRENA (2024) also reports an estimated 0.35 Mt yr^{-1} from coconut shell and husk through the Fischer–Tropsch pathway, resulting in a broader coconut-derived SAF potential of approximately 0.62 MT yr^{-1}. However, this combined value is not directly comparable to the present study, which is limited to NSC-coconut oil (CNO) via the HEFA pathway. The discrepancy between the present study and the comparable IRENA estimate may be attributed to differences in geographical coverage, feedstock resource estimation, conversion assumptions, and data vintage.

Specifically, the present study applies a 30% NSC rejection rate and a coconut-oil-to-SAF conversion factor of 0.0274 kg CNO MJ^{-1} SAF, whereas IRENA utilizes a preliminary regional assessment and assumes a SAF yield of approximately 0.48 t SAF per tonne of feedstock for the HEFA pathway. These methodological differences, combined with the limited availability of recent, comprehensive NSC data, may explain the remaining variance in estimated SAF potential. More broadly, the ASEAN 2050 SAF Outlook (GHD, 2026) projects a substantially larger Philippine SAF supply potential under supportive policy and investment conditions, reaching approximately 1.1 million barrels per day by 2030 and 1.3 million barrels per day by 2050. However, this estimate includes multiple agricultural and sustainable forestry feedstocks and SAF pathways, and therefore serves as regional context rather than a direct benchmark for NSC-CNO-based HEFA SAF.

Table 1: Comparison of SAF potential estimates and key methodological assumptions

Parameter	NSC-PH based scenario	IRENA (2024)	ASEAN 2050 SAF Outlook (GHD, 2026)
Scope	NSC-CNO → HEFA SAF in Davao, Northern Mindanao, and Zamboanga Peninsula; national potential subsequently scaled	Southeast Asian assessment of NSC-derived oil → HEFA; also considers coconut shell/husk → FT	ASEAN-wide SAF supply outlook covering Cambodia, Indonesia, Lao PDR, Malaysia, Philippines, Thailand, and Vietnam; considers multiple agricultural and sustainable-forestry feedstocks
NSC/rejection rate	30% NSC rejection	30% NSC assumption	Not specified as a single NSC rejection rate; broader multi-feedstock assessment
Conversion assumption	0.0274 kg CNO MJ^{-1} SAF	~0.48 t SAF/t feedstock for HEFA	Pathway-specific modelling; no directly comparable NSC-CNO → HEFA conversion factor reported
Resulting estimate	82,812 MT yr^{-1} from three regions; ~0.21 Mt yr^{-1} national equivalent	0.27 Mt yr^{-1} from NSC oil via HEFA; 0.62 Mt yr^{-1} including shell/husk via FT	~1.1 million barrels day^{-1} Philippine SAF supply potential by 2030; ~1.3 million barrels day^{-1} by 2050
Comparability		Directly comparable at the NSC-oil/HEFA level; broader 0.62 Mt value is not directly comparable	Contextual comparison only because it includes multiple feedstocks and pathways

Note: *The national-equivalent estimate of ~0.21 Mt yr^{-1} was calculated by scaling the present study's 82,812 MT yr^{-1} regional SAF potential, which represents approximately 39.6% of the estimated national NSC resource. IRENA's 0.62 Mt yr^{-1} value includes both NSC-oil/HEFA and coconut shell/husk/FT and should therefore not be treated as an equivalent NSC-CNO/HEFA estimate. The ASEAN 2050 SAF Outlook provides a broader multi-feedstock supply outlook rather than an NSC-specific estimate.*

Spatial Distribution of Potential NSC Volumes Across Philippines Border

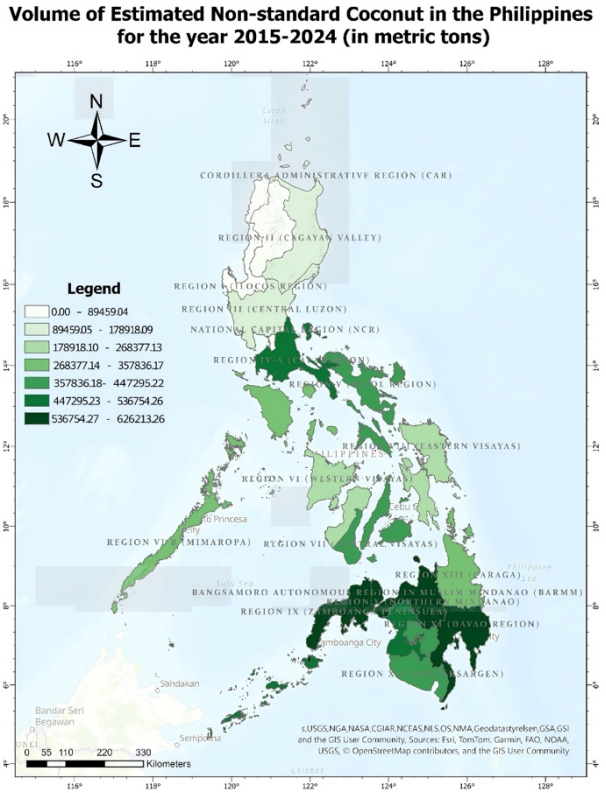


Figure 7: Spatial distribution of the estimated cumulative production of potential non-standard coconuts (NSC), in metric tons, across the Philippines, for the period 2015-2024.

The Philippines' archipelagic location and tropical climate yield abundant tropical fruits, including coconuts. It ranks 2nd among the world's largest exporters of coconuts. In this regard, non-standard availability across its boundaries for the coconut plantation makes a promising contribution to its local context. With NSC becoming a highlighted feedstock to ease the food and fuel dilemma in oil-based derivation to SAF, it gained global interest for a feasible assessment.

Figure 7 shows the distribution of NSC availability across the Philippines, particularly at the regional level, which contributes to the overall viable NSC volumes projected to support SAF production in the local context. Through hotspot analysis, the Mindanao area, particularly the Davao Region, Northern Mindanao, and Zamboanga Peninsula, shows dark green shades that clearly indicate abundant achievable NSC volumes, with dense availability ranging from 536,754.27 to 626,213.26 MT [nut]. Based on Appendix Table 8, a total of 1.75 MMT [nut] is accounted for in the Top 3 coconut-producing regions stated, which represents a 39.6% contribution to the total potential volume from the Philippines, which is 4.42 MMT [nut], placing these regions with the highest percentage for SAF production through NSC. It is also important to note that regions within the Luzon and Visayas boundaries contribute to the optimistic availability of NSC initiated for SAF production in the country, covering the remaining contribution rate of 60.40%.

Overall, NSC is a feasible feedstock, and the Philippines can be a leading contributor to the global SAF market under CORSIA. It is also a valuable by-product for producing jet fuel for the aviation sector, reducing carbon emissions compared to the conventional fuels currently used in the market.

Spatial Distribution of Estimated Potential Volumes of Non-Standard Coconut in Top 3 Producing Regions in the Philippines (Region IX, X, and XI)

A. Region IX (Zamboanga Peninsula)

The intensified map illustrates the potential contribution of Region IX (Zamboanga Peninsula) to meeting demand for non-standard coconut, in line with ICAO-CORSIA's sustainability schemes for SAF. It groups the provinces into three production ranges, each represented by light-to-dark shades, indicating which areas yield higher NSC volumes. The data estimates were provided for a 10-year analysis period from 2015 to 2024 to ensure data integrity and credibility, and to average and account for variations across each year.

In line with this, Figure 8 shows a diverse spatial distribution of NSC production across Region IX, with Zamboanga del Norte exhibiting the highest estimated volume, ranging from 219,906.64 to 245,008.32 MT, followed by Zamboanga del Sur with 71,256.82 to 219,906.64 MT, while Zamboanga Sibugay recorded the lowest estimates, ranging from 0.00 to 71,256.82 MT. These findings establish a baseline of provincial feedstock availability and demonstrate substantial spatial variability in NSC resources, thereby supporting downstream resource management and prioritization of SAF feedstocks that do not compete with food markets. The total estimated NSC volume of 536,171.78 MT for Region IX further highlights the region's strategic importance as a potential biomass source for SAF development.

Among the provinces, Zamboanga del Norte emerges as the most geographically reliable feedstock cluster and may serve as a priority aggregation zone for the collection, sorting, and distribution of NSCs within an integrated SAF supply chain. Concentrating infrastructure investments, such as collection centers, transportation networks, storage facilities, and pilot-scale processing hubs, within high-density resource areas could improve logistics efficiency, reduce transportation costs, and maximize feedstock recovery while avoiding inefficient capital allocation in low-yield locations. Although only a fraction of the estimated NSC resource may ultimately be recoverable, the results underscore the importance of systematic logistics planning and spatial prioritization to support future SAF deployment. This interpretation is consistent with the findings of IRENA (2024), which indicate that achieving SAF targets in Southeast Asia, including the Philippines, will require a high rate of feedstock mobilization, in which available biomass resources are efficiently collected, processed, and converted through coordinated supply chain systems.

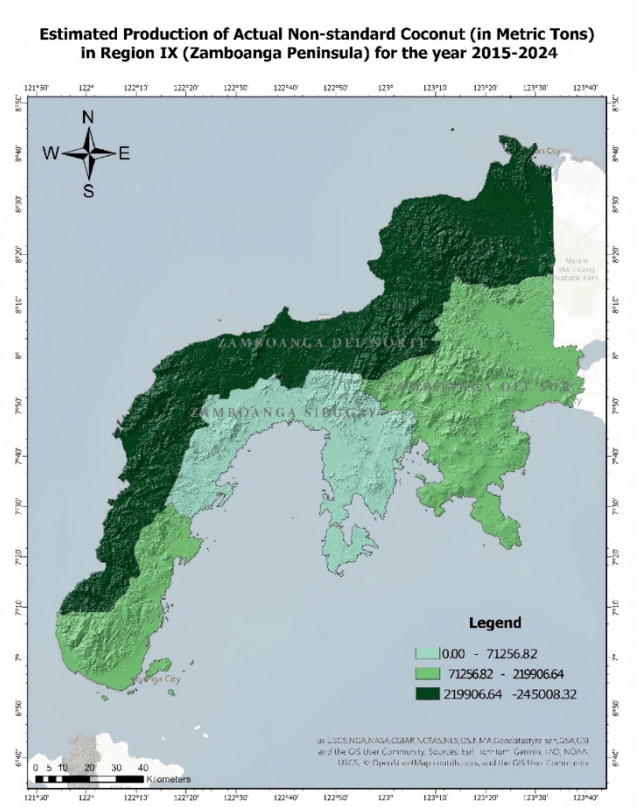


Figure 8: Spatial distribution of the estimated cumulative production of potential non-standard coconuts (NSC), in metric tons, across Region IX (Zamboanga Peninsula), Philippines, for the period 2015-2024.

B. Region X (Northern Mindanao)

Subsequently, the concentrated non-standard coconut (NSC) volumes in Region X (Northern Mindanao) comprise five provinces: Bukidnon, Camiguin, Misamis Occidental, Misamis Oriental, and Lanao del Norte. As shown in Figure 9, the spatial distribution demonstrates distinct intra-regional variation in NSC production, reflecting differences in coconut production intensity across the provinces. Lanao del Norte exhibits the highest estimated NSC production, ranging from 170,671.54 to 174,609.52 MT, indicating its potential as the primary feedstock source in Region X due to its extensive coconut-growing areas and established quality management practices.

In contrast, Misamis Occidental and Misamis Oriental fall within the moderate-to-high production class (163,604.87–170,671.53 MT), suggesting that these provinces could function as complementary feedstock supply zones to support a regional aggregation network centered on Lanao del Norte. Meanwhile, Bukidnon and Camiguin recorded the lowest estimated NSC production (0–14,561.32 MT), reflecting the predominance of upland agriculture and other cropping systems over coconut cultivation, thereby limiting their contribution to the regional feedstock supply.

Region X contributes an estimated 552,906.16 MT of NSCs, differing by roughly 3.1% from the estimated production in Region IX, highlighting its significant potential as a sustainable biomass resource for SAF production. The concentration of feedstock in Lanao del Norte provides a strong basis for prioritizing the province as a strategic aggregation hub, where investments in collection centers, storage facilities, transportation networks, and pilot-scale processing infrastructure could maximize feedstock recovery and improve supply chain efficiency.

Likewise, the proximity of Misamis Occidental and Misamis Oriental offers opportunities to establish an integrated regional collection network that minimizes transportation costs while ensuring a reliable feedstock supply. These spatial insights provide policymakers and private investors with a practical framework for prioritizing infrastructure development in high-yield areas, thereby reducing investment risks and avoiding inefficient capital allocation in provinces with limited biomass availability. Furthermore, the multi-year dataset offers a robust basis for long-term planning by demonstrating relatively stable feedstock availability despite annual production fluctuations, supporting future logistics optimization, traceability systems, and sustainable feedstock mobilization consistent with the recommendations of the ICC (2025).

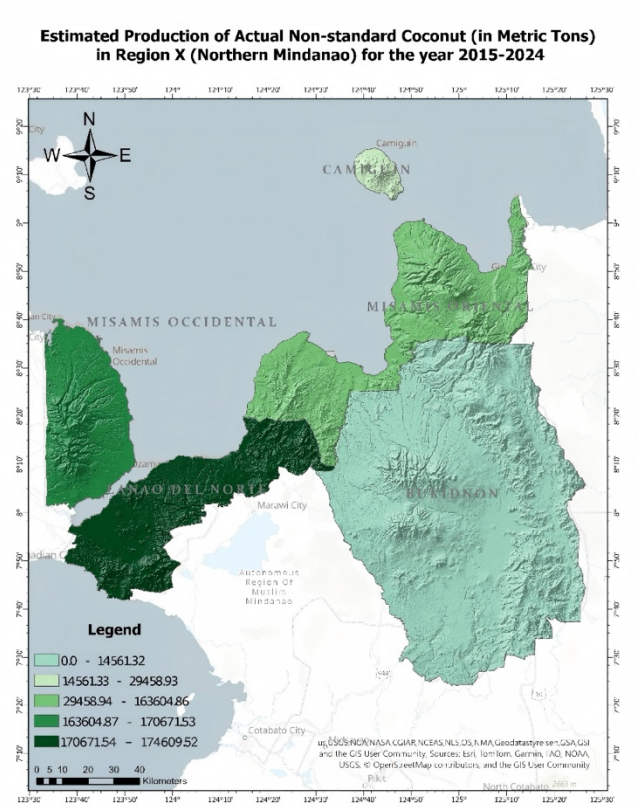


Figure 9: Spatial distribution of the estimated cumulative production of potential non-standard coconuts (NSC), in metric tons, across Region X (Northern Mindanao), Philippines, for the period 2015-2024.

C. Region XI (Davao Region)

Among the top 3 regions, the Davao region recorded the highest NSC potential contribution, amounting to 659,691.25 MT, encompassing the provinces of Davao de Oro, Davao del Norte, Davao del Sur, Davao Occidental, and Davao Oriental. These areas are mapped, showing the occurrence of NSC based on its dense production viability (see Figure 10). The results show the highest NSC production in Davao del Sur, which falls within the uppermost class range (197,539.17 to 218,826.58 MT), indicating the zone as the primary feedstock source in the region. In this regard, large records are particularly evident in its copra-based value chains, which utilize a large fraction of coconuts, even when physically characterized as non-standard, such as sprouted, rotten, cracked, or small-sized.

Positioned as the secondary leading producer, Davao Oriental exhibits NSC production levels (123,759.04 to 197,539.16 MT) and is regarded as a substantial contributor of feedstock,

which can also be added to the supply to enhance the collectability of the raw material. Moreover, Davao del Norte and Davao Occidental are observed to fall within the potential range of 54,738.95 to 123,759.03 MT.

These volumes are lower than those of the leading and secondary highest contributors, which profile NSC with only a few accounts. Despite having the largest geographical area, Davao de Oro records the lowest accountable NSC production, ranging from 0 to 54,738.94 MT. However, despite low records, this relatively small volume still meets the NSC production baseline at one collection point: no more than 120 MT (ICC, 2025).

Significantly, Davao del Sur, as the primary contributor of the highest NSC volumes, represents a strategically feasible aggregation zone for the efficient collection, sorting, distribution, and processing of feedstock in accordance with the standardized quality requirements outlined by the ICC (2025). The concentration of NSC resources within the province provides a practical basis for prioritizing infrastructure investments, including collection centers, storage facilities, transportation networks, and pilot-scale processing plants, thereby enabling a more focused and cost-efficient collection network. By directing investments toward high-density feedstock clusters, policymakers and private investors can optimize logistics, maximize feedstock recovery, and reduce the risk of inefficient capital allocation in areas with limited biomass availability. Consequently, the identified hotspot serves not only as a reliable feedstock source but also as a decision-support framework for developing an integrated and economically efficient NSC supply chain for sustainable aviation fuel production.

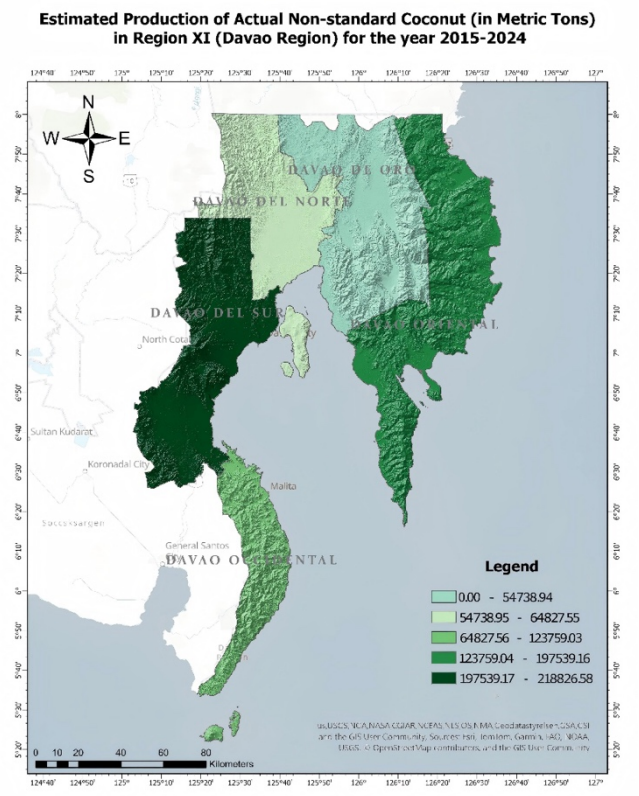


Figure 10: Spatial distribution of the estimated cumulative production of potential non-standard coconuts (NSC), in metric tons, across Region XI (Davao Region), Philippines, for the period 2015-2024.

CONCLUSION

A 20-hectare aggregation scenario was optimized to generate reliable local estimates for non-standard coconuts (NSC) as a non-food, oil-based feedstock for sustainable aviation fuel (SAF). At this collection point, the copra-making facility can potentially sort 18.9 MT and 75.6 MT of NSC annually. This supply adheres to ICC (2025) requirements, which restrict collection to no more than 10 MT per month or 120 MT per year, remaining below the CORSIA high-risk threshold and meeting low-audit-risk standards. This volume can yield approximately 3.58 MT of SAF per year via the HEFA process, indicating that NSC coconut oil is a substantial supplementary feedstock for achieving CORSIA's sustainability objectives in aviation. The Davao Region showed the highest SAF potential contribution at 31,239.25 MT, driven by its numerous collection points, which require 8,726 hubs to achieve this SAF output.

Hotspot analysis identified Davao Region, Northern Mindanao, and Zamboanga Peninsula as the top three contributors, with Davao Region leading in SAF potential. Provinces such as Davao del Sur, Lanao del Norte, and Zamboanga del Norte are critical for NSC collection and SAF supply chain development, collectively accounting for 1.75 MMT [nut], excluding production from Luzon, the Visayas, and other Mindanao areas. Beyond NSC availability, the study identifies challenges in sorting, classifying, and transporting coconuts post-harvest. Mixing NSC with standard coconuts persists because of economic limitations and inadequate sorting infrastructure. Establishing dedicated NSC sorting centers, aggregation hubs, and traceable collection systems is essential for maximizing NSC utilization in compliance with CORSIA regulations.

Sensitivity analysis showed that estimated SAF potential depends on the assumed NSC rejection rate. Across rejection-rate scenarios of 20%, 25%, 30%, 35%, and 40%, combined SAF potential ranged from approximately 55,208 to 110,416 MT, compared to 82,812 MT under the 30% base-case scenario. This variability underscores the uncertainty of applying a uniform rejection rate across production years and emphasizes the necessity for Philippine-specific, multi-season NSC generation measurements. However, these sensitivity results do not affect the identification of the three priority regions or NSC's overall potential as a supplementary SAF feedstock.

In conclusion, non-standard coconuts represent a practical, low-risk, and sustainable feedstock that can facilitate SAF development in the Philippines, support rural communities, and advance the circular bioeconomy. The spatial and volumetric data generated by this research can inform future studies on life-cycle assessment, co-processing, logistics, and policy, positioning NSC as a robust foundation for the Philippines' contribution to global aviation decarbonization.

ACKNOWLEDGMENTS

The author would like to extend sincere gratitude to Dr. Elmar M. Villota, as well as to the committee behind the study's success, the advisers, and the panel members - Dr. Wendy C. Mateo, Dr. Melba D. Denson, and Dr. Carolyn Grace S. Almerol - for their unwavering support and guidance, providing valuable insights and sharing their expertise for lasting impact in greener energy.

It is also hereby acknowledged that the reliable cooperation of the Philippine Coconut Authority, Regional Offices (IX, X, and XI), the Philippine Statistics Authority (PSA), Coconut Cooperative Organizations, and Coconut Farmers was appreciated in

significantly contributing to credible data collection and responding with knowledge during field surveys and farm practices on-site interviews.

Without financial support and academic benefits, the author would not have possibly completed this academic journey. A heartfelt gratitude to the DOST-ERDT program for providing full support throughout the research process.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

CONTRIBUTIONS OF INDIVIDUAL AUTHORS

K.M.B.: Conceptualization, Methodology, Investigation, Data Curation, Formal Analysis, Writing – Original Draft.
W.C.M.: Supervision, Validation, Review, and Editing.
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APPENDICES

APPENDIX TABLES

I. Assessment Inventory from Feedstock Collection Point

Table 1: Detailed calculation of NSC-copra production based on one collection point (20-ha coconut farm area) to SAF potential scenario

ESTIMATED COPRA PRODUCTION FROM NON-STANDARD COCONUT						
Activity	Estimation	Output	Unit	Notes	Total	Unit
Collection						
Area = 1 ha	100 trees	2100	nuts/quarterly	With a spacing of 10 by 10 m, harvested every 3 months, for 1 month there is a fruiting of 1 bunch, and for every 1 bunch, there are 7 nuts fruited in actual farming practice	8,400	nuts/annually
Aggregation = 20 ha	2000 trees	42000	nuts/quarterly		168000	nuts/annually
Non-Standard Allocation = 30%	Weight = 1-2 kg (Gurathne et al., 2018)	12600	nuts/quarterly		50400	nuts/annually
Dehusking						
Weight of NSC	too small = 0.8 kg (Tooy et al., 2025) too old or rotten = 0.36 kg (Kathari et al., 2024) cracked = 1.5 kg (Gunarathne et al., 2018) sprouted = 1.5 kg (Gunarathne et al., 2018)	18.90	MT/quarterly	The weighted values from different literatures were cited for the scenario of NSC in the Philippines farm context	75.60	MT/annually
Weight of Husk	45% (Obeng et al., 2020; Gunarathne et al., 2018)	8.51	MT/quarterly	Utilized 40% kiln drying and 60% geonets	34.02	MT/annually
Weight of Shell	20% (Gunarathne et al., 2018)	3.78	MT/quarterly	Utilized for charcoal making	15.12	MT/annually
Weight of Coconut Water	9% (Gunarathne et al., 2018)	1.70	MT/quarterly	Underutilized	6.80	MT/annually
Weight of Coconut Meat (NSC)	26% (Gunarathne et al., 2018)	4.91	MT/quarterly	Utilized for copra making	19.66	MT/annually
Drying						
Average Initial Moisture	47% FW (Troy, Langi, & Lomo, 2025)			This is averaged moisture experimented based on the study, "Potential of Non-Standard Coconut as a Raw Material for Bioenergy Production"		
Average Dried Weight	6% DW (Magadia et al., 2025)			Utilized for the estimation of copra using Moisture Content Formula		

Dried Copra		1.85	MT/quarterly	Used for extraction of coconut oil	7.39	MT/annually
Deshelling/Scooping						
Weight of Shell	20% (Gunarathne et al., 2018)	2.52	MT/quarterly	After drying, scooping is manually done to separate the meat from the shell	10080	kg/annually
Oil milling						
Ratio of copra to produce CCO into 1 MJ functional unit	0.07361 kg of copra is to 0.046 kg of CCO	1.73	MT CCO/quarterly	This is calculated in the 1 MJ unit of SAF potential using NSC as feedstock	6.93	MT CCO/annually
SAF Potential						
HHV of CNO/CCO (Bui et al., 2025)	42.1 MJ/kg	0.89	MT/quarterly	The calculated 1 MJ SAF from the estimated CCO is 37,639.57 MJ/quarterly and 150558.28 MJ/annually	3.58	MT/annually

Table 2: SAF potential from the top three (3) regions NSC volumes estimated

Region	NSC_MT	Output	Unit	Notes
Zamboanga Peninsula	536171.78	25390.15	MT/annually	The estimate of 75.6 tons NSC for 3.58 tons of SAF
Northern Mindanao	552906.16	26182.6	MT/annually	
Davao Region	659691.25	31239.35	MT/annually	

Table 3: Potential collection points from the top three (3) regions NSC volumes estimated

Region	NSC_MT	Output	Unit	Notes
Zamboanga Peninsula	536171.78	7092	-	The estimate of NSC total divided by the 75.6 tons from aggregated stream sample
Northern Mindanao	552906.16	7313	-	
Davao Region	659691.25	8726	-	

Table 4: NSC volumes availability in Region IX – Zamboanga Peninsula Provincial Level (2015-2024)

PROVINCE	COCO_PROD_MT	NSC_MT
Zamboanga del Norte	816694.3890	245008.3167
Zamboanga del Sur	733022.1428	219906.6428
Zamboanga Sibugay	237522.7240	71256.8172
TOTAL		**536171.7767**

Table 5: NSC volumes availability in Region X – Northern Mindanao Provincial Level (2015-2024)

PROVINCE	COCO_PROD_MT	NSC_MT
Bukidnon	48537.74	14561.3226
Camiguin	98196.43	29458.9284
Lanao del Norte	582031.73	174609.5184
Misamis Occidental	568905.107	170671.5321
Misamis Oriental	545349.53	163604.859
TOTAL		**552906.1605**

Table 6: NSC volumes availability in Region XI – Davao Region Provincial Level (2015-2024)

PROVINCE	COCO_PROD_MT	NSC_MT
Davao de Oro	182463.14	54738.9426
Davao del Norte	216091.83	64827.5475
Davao del Sur	729421.92	218826.5757
Davao Occidental	412530.0867	123759.026
Davao Oriental	658463.86	197539.1565
TOTAL		**659691.2483**

Table 7: Detailed NSC calculations for the Top 3 regions in the Philippines – provincial level (2015-2024)

	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	Average
	Annual	Annual	Annual	Annual	Annual	Annual	Annual	Annual	Annual	Annual	
REGION IX (ZAMBOANGA PENINSULA)	1682120.60	1529763.09	1700249.57	1771941.00	1746948.99	1746036.45	1800694.99	1845408.31	1847480.29	1819935.58	1749057.89
Zamboanga del Norte	784076.35	665775.27	780648.41	849559.15	838702.65	842183.40	860773.61	845328.38	854564.05	845332.62	816694.39
Zamboanga del Sur	481633.82	462859.75	503165.35	515629.05	491527.73	483955.17	508623.38	540281.94	719983.44	713493.31	542115.29
Zamboanga Sibugay	202975.43	204660.85	232234.20	223116.30	230195.60	233304.96	245153.47	269543.99	272932.80	261109.64	237522.72
City of Zamboanga	213435.00	196467.22	184201.61	183636.50	186523.01	186592.92	186144.53	190254.00	..	..	190906.85
REGION X (NORTHERN MINDANAO)	1851702.14	1802402.56	1807046.16	1839731.49	1836112.35	1858779.80	1864904.24	1872149.94	1888759.82	1808616.85	1843020.54
Bukidnon	53393.30	40216.30	39316.07	48937.24	51156.75	48605.14	49712.67	51881.03	52821.30	49337.62	48537.74
Camiguin	102466.80	100504.11	97018.59	98592.25	97233.87	96528.02	100713.89	96082.78	98690.24	94133.73	98196.43
Lanao del Norte	589234.77	580104.59	579396.00	580649.00	580500.92	581036.00	581036.00	581354.00	583078.00	583928.00	582031.73
Misamis Occidental	582151.02	570075.20	569897.50	571749.00	565150.02	564124.93	564747.79	564716.96	568848.46	567590.19	568905.11
Misamis Oriental	524456.25	511502.36	521418.00	539804.00	542070.79	568485.70	568693.90	578115.17	585321.82	513627.31	545349.53
REGION XI (DAVAO REGION)	2246187.53	1894663.09	1886599.87	1932559.23	1931955.46	1962696.74	1983241.63	2012425.16	1987785.60	1969491.77	1980760.61

Davao de Oro	185134.32	181777.57	182148.29	182218.06	181877.25	183190.17	182925.03	183378.19	181040.37	180942.17	182463.14
Davao del Norte	228876.52	219317.63	216663.79	220929.63	211770.17	216388.87	210606.66	213351.71	211511.27	211502.00	216091.83
Davao del Sur	872895.86	586774.66	565912.61	615674.17	218404.09	231029.82	231455.38	239812.58	539400.15	532950.77	463431.01
Davao Occidental	..	..	..	..	406648.89	405438.08	412739.45	417973.04	415713.05	416668.01	412530.09
Davao Oriental	703640.98	653887.58	666056.13	657165.43	657322.86	660674.28	660301.15	658040.56	640120.75	627428.83	658463.86
City of Davao	255639.85	252905.65	255819.05	256571.94	255932.19	265975.52	285213.96	299869.09	..	..	265990.91

Table 8: Average calculation of NSC availability volumes across Philippine boundary

Regions	10-year estimates (2015-2024)	
	Production	NSC 30%_MT
Autonomous Region in Muslim Mindanao (ARMM)	1,344,995.27	403498.5815
Cordillera Administrative Region (CAR)	1,058.20	317.4602308
National Capital Region (NCR)	0	0
Region I (Ilocos Region)	43,261.90	12978.56977
Region II (Cagayan Valley)	77,163.69	23149.10769
Region III (Central Luzon)	128,720.38	38616.11262
Region IV-A (CALABARZON)	1,504,888.16	451466.4489
MIMAROPA Region	794,546.32	238363.8974
Region IX (Zamboanga Peninsula)	1,740,293.31	522087.9932
Region V (Bicol Region)	1,167,643.23	350292.9692
Region VI (Western Visayas)	506,223.08	151866.9249
Region VIII (Eastern Visayas)	1,218,588.71	365576.6121
Region VII (Central Visayas)	402,825.50	120847.6486
Region X (Northern Mindanao)	1,838,591.48	551577.4428
Region XI (Davao Region)	2,087,377.52	626213.2567
Region XII (SOCCSKSARGEN)	1,111,067.39	333320.2175
Region XIII (Caraga)	767,177.06	230153.118

II. Lifecycle Inventory from Feedstock Collection to Jet Fuel Combustion

Table 9: Detailed calculation of NSC to SAF conversion following the functional unit (1 MJ of SAF)

Functional Unit			
Note: Conversion of coconut oil to 1 MJ of SAF			
Material	**Quantity**	**Units**	**Notes**
LHV	44	MJ/kg	DIRECTIVE (EU) 2018/ 2001 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL - of 11 December 2018 - on the promotion of the use of energy from renewable sources
Bio Jet Fuel (SAF)	1000	kg SAF	Vasquez et al., 2019
SAF energy (1-ton CNO)	44000	MJ SAF	Manual computation
1 MJ SAF to CNO	0.046006591	kg CNO	Manual computation
Conversion to ton	4.60066E-05	ton CNO	Manual computation
Note: Normalizing material balance for copra to 1 MJ SAF			
Copra	62.50%	oil yield efficiency	Subroto et al., 2020; Heurietta et al., 2022
Copra for 0.046 kg of CNO	0.073610545	kg Copra	Manual computation
Conversion to ton	7.36105E-05	ton Copra	Manual computation
Drying efficiency	56.38%	copra	Manual computation
NSC meat to provide 0.058 kg of copra	0.13056145	kg NSC meat	Manual computation
Conversion to ton	0.000130561	ton	Manual computation
Note: Normalizing material balance for NSC to 1 MJ SAF			
1 NSC nut	1.04	kg	Manual computation
1 nut to meat	26%	by weight	Gunarathne et al., 2018

1 nut to meat	0.2704	kg		Manual computation
No. of NSC needed for 0.131 kg of meat	0.482845599		~1	nearly 25.93% of the meat from 1 nut of NSC will only be used to supply a 1 MJ SAF unit

APPENDIX FIGURES

III. Farm Practices Validation from the Top 3 Coconut Producing Regions in the Philippines



Figure 1: Field visitation and peer-review discussion on non-standard coconut assessment in the Philippine Coconut Authority XI – Davao City



Figure 2: Farm Practices On-Site Verification at Tagakpan Balingayin Microfarmer Association (TABAMFA), one of the primary cooperatives in Davao City



Figure 3: Evidence of non-standard coconut availability in the field underutilized, classified abundantly were rotten, cracked, and sprouted



Figure 4: Evidence of non-standard coconut processing potential in the *tapahan* dried into copra using traditional method of smoke-kiln drying system



Figure 5: Actual harvesting practice manually of coconut, also known as *sungkit* or pulling method with a sharp material attached to the bamboo wood



Figure 6: Field validation collaborating with Philippine Coconut Authority X (Provincial and Regional), also valuable insights from Regional Field Office X – Misamis Occidental



Figure 7: Field validation collaborating with Philippine Coconut Authority IX (Provincial) – Pagadian City, Zamboanga Del Sur



Figure 8: Farm Practices On-Site Survey Interview at Bulawan Coconut Farmers Agriculture Cooperative (BCFAC) together with the Chairperson



Figure 9: Copra making using their direct heat smoke-kiln drying set up at BCFAC coconut farm aggregation site