Journal of Clean Technology

REVIEW ARTICLE

Energy Efficiency in Palm-Based Food Production Processes in margarine industry through the Utilization of Palm Fiber as Solid Biomass in Boiler Systems: A Comprehensive Review

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Received: 20 May 2025, Revised: 22 June 2025, Accepted: 08 July 2025, Published: 01 August 2025

Abstract

The increasing demand for margarine, especially in palm oil producing countries like Indonesia, raises concerns about energy consumption and environmental sustainability. This review discusses the potential of palm fiber, a lignocellulosic byproduct of crude palm oil extraction, as a solid biomass fuel to improve energy efficiency in margarine processing industries. A systematic literature review was conducted by analyzing more than sixty peer reviewed journal articles, technical reports, and case studies to evaluate the feasibility and impact of palm fiber utilization. Based on various studies, palm fiber contains 47.9 percent cellulose, has a calorific value of 17.2 megajoules per kilogram, and shows low ash and moisture content, making it suitable for combustion in industrial boilers. Emission data indicate reductions in carbon dioxide, nitrogen oxides, and sulfur oxides compared to fossil fuels, with potential greenhouse gas savings of 0.098 tons of carbon dioxide per gigajoule and sulfur oxide reductions of up to ninety percent. Economically, palm fiber offers cost savings of up to forty percent, with a levelized cost of energy around six United States dollars per gigajoule and a payback period of less than five years. The application of drying and co firing technologies, supported by policy incentives such as Indonesia's capital expenditure assistance, could enhance adoption. Research gaps remain in terms of long term boiler corrosion and industrial scale briquetting. Overall, palm fiber supports circular economy practices and aligns with SDG 7, 12, and 13, contributing to cleaner energy transitions in palm oil based food production systems.

Keywords: biomass energy, boiler efficiency, circular economy, margarine industry, palm fiber

Introduction

The increasing global demand for energy and sustainable food production has intensified the need for environmentally friendly industrial practices. The global consumption of margarine has shown a consistent upward trend due to its affordability, longer shelf life, and perceived health benefits compared to traditional butter. As the demand for processed and convenience foods increases, margarine has become a widely used fat-based ingredient across bakery, confectionery, and foodservice industries worldwide [1]. Global margarine demand is projected to grow by 5% annually until 2033, with Indonesian consumption rising from 13.54 thousand tons in 2014 to 39 thousand tons in 2018 [2]. Palm oil is the dominant base oil in margarine formulations due to its semi-solid characteristics at room temperature, cost efficiency, and high oxidative stability [3]. Consequently, the margarine industry has become an integral downstream component of the palm oil value chain, particularly in major palm oil-producing countries such as Indonesia and Malaysia. As margarine is primarily produced using palm oil due to its favorable properties and cost-efficiency, Indonesia holds a strategic position in the global supply chain as the world's largest crude palm oil (CPO) producer, accounting for 62% of global output, followed by Malaysia with a

33% share [4]. However, this increasing demand also puts pressure on the industry's energy consumption, especially in thermal processing operations.

The production process of margarine involves several energy intensive operations, including preparation of the aqueous and oil phases, emulsification, cooling and crystallization, and packaging [5]. Most of these stages rely heavily on thermal energy, typically supplied by steam from fossil fuel based boilers [6]. As energy represents one of the most significant operational costs especially in thermal processing units energy efficiency becomes a key focus for manufacturers seeking to reduce production costs and improve competitiveness. Beyond cost implications, the use of fossil energy in margarine production also raises environmental concerns. The sector's reliance on fossil-based thermal energy contributes to greenhouse gas (GHG) emissions, thereby increasing its carbon footprint. With mounting pressure from regulatory authorities and environmentally conscious consumers, food industries are being urged to adopt low-emission and sustainable energy practices [7]. Globally, the food processing, production, and consumption sector accounts for more than 20% of anthropogenic GHG emissions, releasing an estimated 9800–16,900 million tonnes of CO_2 annually, a figure projected to rise to 30% by 2050 [8]. For margarine manufacturers, this presents both a challenge and an opportunity to transition toward low-carbon energy alternatives, particularly in their steam generation systems. In Indonesia, the margarine industry accounts for approximately 18-22% of the thermal energy demand in the palm-based food processing sector, with steam generation for emulsification and crystallization being the most energy-intensive stages [7]. This significant energy footprint coupled with the sector's reliance on fossil fuels amplifies both operational costs and environmental impacts.

As margarine production is tightly linked to the palm oil industry, utilizing palm-derived biomass offers a closed-loop energy solution. One promising pathway is the integration of renewable biomass sources, especially those derived from internal or nearby industrial waste streams. In addition, the lifecycle of palm oil production harvesting, milling of fresh fruit bunches (FFB), and planting creates a massive amount of solid waste in the form of oil palm biomass (OPB) [9]. This lifecycle generates over 60 million tons of biomass annually, dominated by empty fruit bunches, fronds, mesocarp fiber, trunks, and shells [10]. This residue is abundant, renewable, and exhibits suitable physical and calorific properties for utilization as solid biomass fuel [11]. Leveraging palm fiber for thermal energy production in margarine plants represents a viable approach to reduce fossil fuel dependency while adding value to waste materials within the same agro-industrial system.

Natural fibers are widely available and more affordable than synthetic alternatives, offering advantages such as lower density and energy requirements, renewability, biocompatibility, and superior strength-to-weight ratio [12]. As a by-product of the palm oil industry this biomass is not only abundant but also underutilized in energy applications especially in the food processing sector such as margarine manufacturing [13]. The chemical composition of different types of palm fiber shows that oil palm frond contains 25.2% hemicellulose, 49.8% cellulose and 20.5% lignin, while oil palm empty fruit bunch (EFB) contains 17.1-22% hemicellulose, 47.9-48% cellulose and 24.9-25% lignin [14]. The porous and rigid surface of palm fibers with a pore size of about 0.7 μm allows for better interaction with the matrix resin, but can also lead to water absorption due to capillary action, which increases their potential use in energy applications [15]. Despite these challenges, palm oil biomass (POB) fibers are used in various industries and as biomass fuel [16].

Over the past two decades, research on the utilization of biomass as an alternative energy source has experienced substantial growth, particularly in the context of biomass derived from agricultural residues [17]. Numerous studies have demonstrated that organic wastes such as rice husks, corn cobs, and sugarcane bagasse possess significant potential as solid fuels for combustion systems and steam boilers, applicable at both small-scale and industrial levels [18]. Within the palm oil industry, palm fiber classified as a solid lignocellulosic residue from the crude palm oil extraction process has been identified as a biomass material with a relatively high heating value and favorable organic content for thermochemical conversion processes [19]. Its application as a boiler fuel has been extensively investigated in the energy sector, particularly in the context of fossil fuel substitution and improving overall thermal energy efficiency in industrial systems [20].

However, most existing studies focus on general biomass utilization or large-scale palm oil processing, with limited attention to palm fiber application specifically in margarine production systems. This review aims to comprehensively evaluate the potential of palm fiber as a solid biomass fuel for boiler systems in the margarine industry. It focuses on assessing the energy potential through analysis of the physical and chemical characteristics of palm fiber, with the goal of enhancing thermal energy efficiency. The review also examines technical, environmental, and economic aspects, including boiler performance, emissions impact, sustainability, and cost-benefit analysis. Additionally, it provides practical and scientific recommendations to support the adoption of biomass energy as part of long-term efficiency and sustainability strategies in the margarine sector, contributing to the advancement of renewable energy technologies circular economy integration, and alignment with SDG 7, 12, and 13 in palm oil-based food production systems.

Materials and methods

Materials

Palm fiber (mesocarp fiber) is a lignocellulosic residue generated during the mechanical extraction of crude palm oil from fresh fruit bunches (FFB). Indonesia, as the world's largest palm oil producer, processed approximately 47,08 million tons of FFB in 2023 [21], yielding an estimated 5.2 million tons of palm fiber annually. Despite this abundance, its utilization as an energy source remains suboptimal, with only 20-30% currently valorized for industrial applications [22].

Chemically, palm fiber consists of lignocellulosic compounds, mainly cellulose (47.93% wt), hemicellulose (14–25% wt), and lignin (13–25% wt) [23]. These macromolecules determine the fiber's energy potential. Its calorific value ranges between 14–18 MJ/kg, depending on drying and storage conditions [25]. The drying process is carried out at a temperature of 105°C for 24 hours to achieve a moisture content of less than 10 wt%. This threshold improves combustion efficiency and prevents microbial degradation. These conditions are in line with biomass preparation standards, where drying at temperatures between 100-110°C for an adequate period of time ensures moisture removal without compromising the structural integrity of lignocellulosic fibers [25]. Moisture content typically lies within 10–15%, while ash content remains under 5% [24]. Its high volatile matter 70–75% kg/m^3 [22], and moderate fixed carbon 15–18% wt [22]. Physically, the fiber exhibits a bulk density of 100-150 kg/m^3 and particle density of 700-900 kg/m^3 [26]. Influencing its handling and combustion behavior in boilers. The fiber's composition is summarized in Table 1.

Table 1. Comprehensive Chemical and Physical Properties of Palm Fiber

Properties	Value	Unit	Reference
Volatile matter	70-75	% wt	[22]
Fixed carbon	15-18	% wt	[22]
Cellulose	47,93	% wt	[23]
Hemicelullose	14-25	% wt	[23]
Lignin	13-25	% wt	[23]
Moisture	10-15	% wt	[24]
Ash content	<5	% wt	[24]
Higher heating value	17,2	MJ/kg	[25]
Bulk density	100-150	kg/m^3	[26]
Particle density	700-900	kg/m^3	[26]

Palm fiber availability in Indonesia is substantial. With over 47 million tons of FFB processed annually, more than 5 million tons of fiber are produced and remain largely underutilized. When incorporated into boiler systems, especially in margarine processing, palm fiber can significantly reduce fossil fuel consumption, operational costs, and emissions. Thus, it offers a technically and economically competitive biomass alternative. To contextualize its fuel quality, Table 2 presents a comparison between palm fiber and other commonly used biomass types.

Table 2. Comparison of Calorific Value of Solid Biomass

Biomass Type	Higher heating value (Mj/kg)	Ash (%)	Moisture (%)	Reference
Palm fiber	17.2	4.1	12.5	[25]
Empty palm bunches	11.5	6.2	62.3	[26]
Rice straw	14.1	18.7	13.2	[27]

Based on Table 2, palm fiber outperforms other biomass types such as rice straw and EFB, particularly due to its lower moisture and ash content. With a calorific value of 14–18 MJ/kg, low slagging potential, and an abundant domestic supply exceeding 5 million tons per year [28], palm fiber is highly suitable for use as industrial boiler fuel. In margarine production, it can replace fossil fuels for steam generation [29], reduce operational fuel costs by up to 30-40% compared to diesel [30], and lower carbon emissions by 0.098 tons of CO_2 per gigajoule of energy produced [29]. These technical, economic, and environmental benefits position palm fiber as a promising biomass alternative.

Methods

1. Research Methodology

To complement the experimental methods, a *systematic literature review* (SLR) in this study was conducted qualitatively, without applying a fixed numerical screening protocol (e.g., PRISMA). Instead, the review was conducted using a structured qualitative literature approach, emphasizing credibility, relevance, and completeness of technical data and focused on identifying high-quality, peer-reviewed journal articles from the last decade (2015–2025) using relevant keywords: *palm fiber*, *biomass fuel*, *pretreatment*, *briquetting*, and *drying process* on Scopus, ScienceDirect, and Web of Science databases.

While no exact initial count of articles is recorded, the final synthesis involved over 60 articles that met relevance and technical quality criteria. The study does not include experimental work and instead consolidates existing experimental findings from previous research to evaluate palm fiber's technical and economic viability as boiler fuel. No primary experiments were conducted in this review. All technical and economic parameters, including briquette formation and boiler performance, are based on prior experimental studies cited in the literature.

2. Pretreatment

The harvested oil palm fruit from plantations in the Sumatra region of Indonesia is transported by truck to palm oil mills, where it undergoes the following processing stages:

The initial stage involves sterilizing the fresh fruit bunches (FFB) using a sterilizer to separate the loose fruits from the empty fruit bunches (EFB) [31]. However, not all loose fruits are detached during this stage, so further separation is carried out using a harvester [32]. The EFBs that have been separated from the loose fruits are conveyed to a storage area and can be utilized as plant fertilizer, while the loose fruits are fed into a digester to extract crude palm oil (CPO) [33]. The skins of the loose fruits exiting the digester become fine fibers. The kernel plant fiber derived from the EFBs and loose fruit skins is used as fuel, while the nuts (palm kernels) discharged from the digester are further processed in a cleaning drum to remove any remaining fibers attached to the nuts [32].

The produced palm fiber undergoes screening using a magnetic separator to remove metallic contaminants, and a mechanical screen to separate non-metallic coarse materials. The cleaned palm fiber is then dried to enhance combustion efficiency [34]. This drying process is carried out until the moisture content is reduced to below 10 wt% over a period of 24 hours at a temperature of 105 °C [35]. After drying, the fiber is shredded using a hammer mill to facilitate the subsequent processing steps and to ensure uniform combustion.

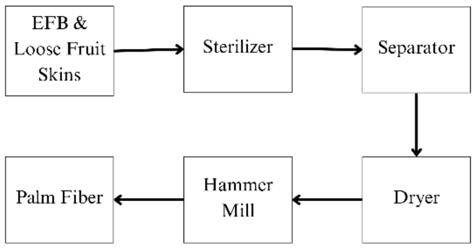

Figure 1. Process of Pretreatment Palm Fiber [31-35]

2. Solid Biomass Fuels Production

In this experiment, a cylindrical briquetting mold made of hardened steel was utilized, with an internal diameter of 19.4 mm and a height of 50.2 mm. The setup also included a 65.0 mm pressing piston and a 10.0 mm stop piston. Briquetting was performed using a manually operated hydraulic press specifically designed for laboratory-scale applications, capable of delivering up to 1000 kg/cm² (equivalent to 98.07 MPa) of pressure. For each bio-briquette, around 10–20 grams of the prepared material mixture was placed into the mold and compacted at a constant pressure of 400 kg/cm² for 2–5 minutes, or until the applied load stabilized. This procedure was consistently applied for the production of all briquettes [35]. The biomass is then packaged and stored in a dry place to avoid moisture absorption.

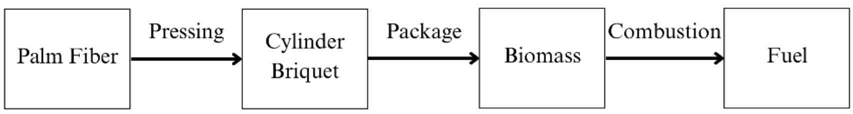

Figure 2. Solid Biomass Fuels Production [35]

3. Characteristics of Solid Biomass Fuels

Thermogravimetric analysis (TGA) was conducted, along with other techniques including scanning electron microscopy (SEM). In this context, SEM was employed to examine morphological characteristics [26].

Results and discussion

3.1. Thermal Properties and Boiler Performance

Thermal efficiency in a boiler system is strongly influenced by the characteristics of the fuel used, especially its heating value, ash content, moisture content, and combustion behavior. Therefore, evaluation of the thermal characteristics of palm fiber as solid biomass is important in assessing its feasibility as an alternative fuel to replace fossil energy in the margarine industry which requires a continuous supply of hot steam. Based on the data in Table 1 and Table 2, palm fiber has a heating value of 17.2 MJ/kg, an ash content of less than 5%, and a moisture content of about 12.5%. These characteristics indicate high potential as a solid fuel in industrial combustion systems. Palm fiber has an ash content of less than five percent, which reduces the risk of slag accumulation during combustion in boiler systems. In addition, X-ray diffraction analysis of ash from palm-based biomass shows the presence of stable minerals such as quartz, albite, and magnesioferrite, indicating high thermal resistance and a lower tendency to form sticky deposits during high-temperature

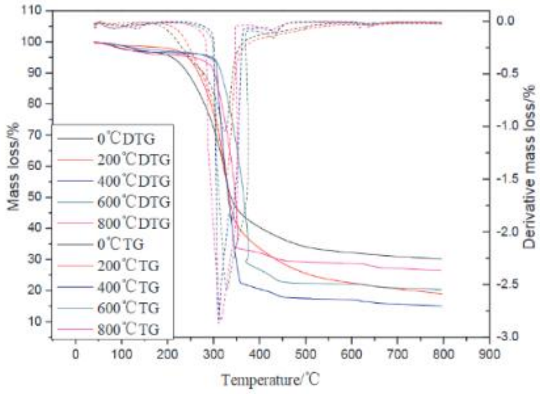

Figure 3. Thermogravimetric Curve Of Palm Fiber And Palm Fiber Char [37].

Thermogravimetric (TG) and differential combustion rate (DTG) analysis results show that palm fiber undergoes a combustion process in three main stages, namely water evaporation (drying), active combustion, and burnout. The active combustion process occurs in the temperature range of 200 to 500 °C, characterized by a significant decrease in mass and an increase in combustion rate, especially in samples carbonized at 400 °C [37]. This indicates that at this temperature, the rate of thermal reactivity reaches a maximum, resulting in a stable combustion flame and minimal residue remaining. Compared to coal, biomass such as palm fiber contains higher volatile matter and lower fixed carbon, which improves ignition but may also increase the release of ash forming elements during combustion [38]. According to the final analysis conducted by Azmi et al. (2021), palm fiber contains 43.38 percent carbon and 6.95 percent hydrogen by weight, both of which significantly contribute to its calorific value, while its nitrogen and sulfur contents were recorded at 0.84 percent and 0.14 percent, respectively, which are low enough to indicate the potential for minimal nitrogen oxide and sulfur oxide emissions during combustion, thus reinforcing its viability as a clean and efficient solid fuel for industrial boiler applications [39].

To further evaluate the applicability of palm fiber as boiler fuel, it is important to compare its thermal performance with other commonly used biomass sources. Table 3 presents a comparative overview of boiler efficiency and thermal output across different biomass fuels.

Tabel 3. Comparative Boiler Efficiency and Thermal Energy Output from Various Biomass Fuels

Fuel Type	Boiler Efficiency (%)	Thermal Energy Output (MJ/hour)	Reference
Palm Fiber (PKS XYZ)	73	44.720	[40]
Palm fiber (Erivianto)	73	69.060	[41]
Corn Cob	72	1800	[42]
Sawdust	84.72	37.326	[43]
Rice Husk	71.6	47.488	[44]

Based on operational data from PKS XYZ, there is unutilized solid waste in the form of palm fiber amounting to 2,600 kilograms per hour, and by using a heating value of 17.2 megajoules per kilogram as listed in Table 1, the potential thermal energy that can be generated reaches approximately 44,720 megajoules per hour or 12.4 megawatt-hours, which demonstrates the feasibility of palm fiber as a reliable heat source for industrial boiler systems [40].Based on calculations by Erivianto et al. (2024), a boiler system with a steam output of 18,000 kilograms per hour and an efficiency of 73 percent requires approximately 16.5 million kilocalories per hour of thermal energy, which can be supplied by 4,172.6 kilograms of palm fiber per hour based on its calorific value of 3,963.44 kilocalories per kilogram, demonstrating the adequacy of palm fiber as a primary biomass fuel for high-capacity industrial steam generation [41]. Compared to other biomass fuels presented in Table 3, such as corn cob, sawdust, and rice husk, palm fiber shows a balanced profile with moderate thermal efficiency and high availability within the palm oil industry. The relatively low thermal energy output reported for corn cob may be attributed to pilot-scale testing in a 500 kW low-temperature fluidized bed combustor operating at 650–700 °C [42]. As the original study focused primarily on alkali emissions and slagging behavior rather than maximum combustion output, the reported value may not be directly comparable to full-scale industrial systems. This highlights the importance of managing alkali-related slagging risks in biomass combustion. In the case of palm fiber, although ash content is relatively low, the presence of alkali-forming minerals may still pose challenges in high-temperature boiler operations, warranting proper combustion temperature control or pre-treatment strategies**.** Although sawdust achieves higher efficiency under co-firing conditions (84.72%), palm fiber remains advantageous due to its ability to function as a standalone fuel without the need for blending or pre-processing. In addition, the use of palm fiber remains a competitive option due to the abundant availability of palm fiber waste in the palm oil industry centers, relatively low transportation costs as it is sourced from internal processes, and strong integration potential in the circular economy concept.

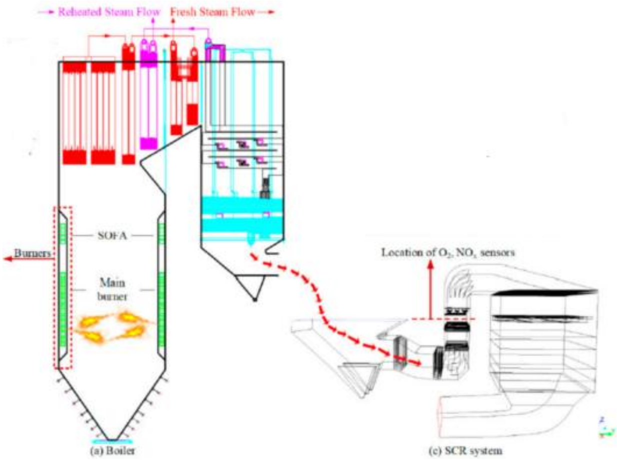

Figure 4. Schematic Diagram Of The Boiler In Industry [45]

In general, combustion in industrial boilers involves the injection of solid biomass fuels such as palm fiber or wood pellets into a combustion chamber, where they are oxidized with a controlled air supply to generate high temperature flue gases. These hot gases transfer heat to water circulating in boiler tubes, ultimately producing steam for industrial applications. Figure 4 illustrates a typical schematic of a solid fuel fired boiler system equipped with burners, flue gas monitoring sensors, and a heat exchange section [45]. In biomass based systems, efficiency and emission testing are typically conducted by monitoring parameters such as flue gas composition, dust particulates, and heat output, as demonstrated in a study utilizing wood pellets as fuel [46]. This approach enables continuous evaluation of performance indicators such as combustion efficiency and pollutant levels, reinforcing the practical viability of biomass, particularly palm fiber, as a sustainable alternative to conventional fossil based fuels in industrial boiler systems.

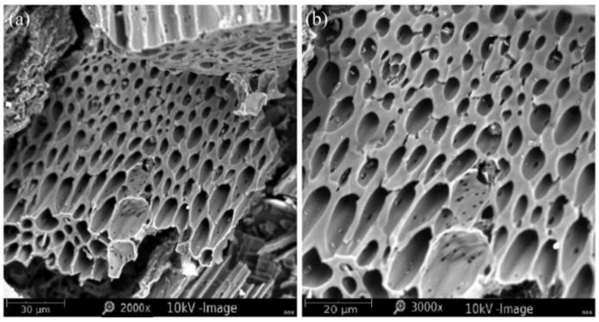

Figure 5. SEM Image Of Biochar At Maximum Yield (Biochar-OP) For Two Magnifications of A × 2000 And B× 3000 [47].

Figure 5 presents scanning electron microscopy images of biochar produced from oil palm fronds using microwave pyrolysis at elevated temperatures. The surface shows a porous structure with thin and clearly defined cell walls, resulting from the release of volatile compounds during thermal decomposition. Although the images are not derived directly from palm fiber, oil palm fronds share similar lignocellulosic characteristics, making their morphological behavior relevant to support the argument regarding combustion performance of palm-based biomass such as palm fiber [47]. Based on the thermal, structural, and compositional characteristics discussed, palm fiber demonstrates strong potential as a stable and efficient solid fuel for industrial boiler systems.

3.2. Emissions and Economic Evaluation

Palm fiber combustion achieves a 0.098 tCO_2/GJ reduction in net CO_2 emissions compared to diesel, reflecting its carbon-neutral cycle [48]. The claim of carbon neutrality for palm fiber is based on the biogenic nature of this fuel. The CO_2 released during combustion is considered part of the natural carbon cycle because it comes from carbon that was previously absorbed from the atmosphere by palm trees during their growth period. In the short-term carbon cycle perspective, net CO_2 emissions from the combustion of this biomass are often considered to be close to zero, so they are generally not counted as new emissions in life cycle assessment (LCA) calculations for the biogenic emissions category [48]. Therefore, the reported CO_2 emissions for palm fiber often only reflect emissions from the supply chain (such as processing and transportation), which is around 0.010 tCO_2/GJ. This value is much lower than the direct emissions from fossil fuels such as diesel.

Its nitrogen content is below 0.1 wt %, NO_2 emissions from palm fiber are approximately 0.20 kg/GJ, or 50 % lower than diesel's 0.40 kg/GJ [49]. Its sulfur content under 0.1 wt % results in SO_x emissions of just 0.08 kg/GJ, a 90 % decrease relative to diesel at 0.80 kg/GJ [50]. Additionally, the low ash content of 4.1 % minimizes fouling and slagging, thereby reducing $PM_{2.5}$ emissions by up to 80 % compared to other biomass fuels [51]. Table 4 presents a comparison between emmision performance for various fuels.

Table 4. Emmision Factors for Various Fuels

Fuel	CO_2 (t/GJ)	NOx (kg/GJ)	SOx (kg/GJ)	$PM_{2.5}$ (kg/GJ)	Reference
Palm fiber	0.010	0.20	0.08	0.15	[48]
Diesel	0.108	0.40	0.80	0.25	[50]
Empty fruit bunch	0.012	0.25	0.10	-	[52]
Rice straw	0.085	0.50	0.30	-	[53]
Coal	0.098	0.60	2.00	1.80	[54]

The levelized cost of energy (LCOE) for palm fiber is USD 6/GJ, about 33 % lower than industrial diesel at USD 9/GJ [55]. These savings translate into 30–40 % reductions in fuel operating costs for a 10 t/h steam boiler, or approximately USD 200,000 per year [56]. Although retrofitting a boiler to burn biomass adding dryers, ash-handling and feeding systems requires a capital expenditure of about USD 200/Kw_{th}. Although the Net Present Value (NPV) of USD 48,846 for a 5 MW palm fiber cogeneration power plant is relatively low in absolute terms, this value reflects the favorable local context, particularly the availability of low-cost biomass fuel with minimal transportation costs and capital incentives. As a comparison, renewable energy projects of comparable scale based on imported biomass or waste-based biofuels, although they may achieve comparable or higher NPVs, generally have longer payback periods and higher operational expenditures [57].

An internal rate of return (IRR) of 9.7 %, and a payback period of under 5 years [57]. Local sourcing from adjacent palm mills keeps transport costs below USD 0.01 per GJ.km^{-1}, further enhancing economic attractiveness [58]. It is crucial to remember that local factors, such as the price of biomass on the market, the distance from supply sources for transportation, labour expenses, and the state of boiler infrastructure, have a significant impact on economic metrics like Net Present Value (NPV) and Levelized Cost of Energy (LCOE). The economic feasibility of biomass-based projects may be diminished in areas with higher biomass prices or greater transportation distances, but it is still typically advantageous when compared to alternatives based on fossil fuels [58]. The economic viability for palm fiber in Table 5.

Table 5. Economic Indicators for Palm Fiber Utilization

Parameter	Value	Reference
LCOE (USD/GJ)	6.0	[55]
Annual savings (USD/10 t/h)	200,000	[56]
Capital Expenditure (USD/kW$_{th}$)	200	[57]
Net Present Value (USD)	48.84	[57]
Internal Rate of Return (%)	9.7	[57]
Payback Period (years)	<5	[57]

Table 6 clearly shows the economic advantages of palm fibre as a biomass fuel. The low LCOE (USD 6/GJ) results in significant annual savings (USD 200,000) for a 10 t/h boiler. Although boiler modification investment is required (USD 200/kW), the 5 MW project promises an NPV of USD 48,846, an IRR of 9.7%, and a payback period of under 5 years. The combination with minimal transportation costs (<USD 0.01 per GJ·km) further strengthens its commercial viability, particularly for factories located close to palm oil waste sources.

3.3. Industrial Feasibility and Strategic Outlook

Palm fiber, as a biomass material, contains moisture levels reaching 30–50%wt in its fresh state [59], which can hinder ignition and reduce combustion temperature[60], thereby lowering combustion efficiency as a significant portion of energy is used to evaporate the moisture [61]. In addition, palm fiber also contains ash with high concentrations of alkali minerals, such as potassium and sodium, which leads to ash fouling and slagging on the surface of heat exchangers in the boiler, thereby reducing heat transfer efficiency and increasing maintenance frequency [62]. To address these challenges, technological solutions such as drying and co-firing processes can be implemented.

The drying process can be carried out using rotary dryers, fluidized bed dryers, or thermal drying by utilizing waste heat recovery from industrial processes to reduce the moisture content to below 10%wt. This significantly improves the calorific value of the biomass and enhances combustion efficiency [63]. Co-firing is a combustion technique that involves the simultaneous burning of palm fiber with fossil fuels (such as coal), aiming to improve operational flexibility and combustion stability. Additionally, co-firing helps lower local combustion temperatures and reduces slag formation [64].

Margarine industries that use palm oil as their primary raw material have significant potential to integrate palm fiber-based biomass combustion systems directly into utility boilers, particularly for process heating and steam generation [65]. The use of palm fiber strengthens the circular economy model, which emphasizes the reutilization of industrial waste as fuel [66]. This reduces dependence on fossil fuels, lowers operational costs, and decreases CO_2 emissions [67]. Carbon footprint analysis in the palm oil industry indicates that the use of biomass (fiber and shell) can significantly reduce emissions by approximately 457 kg CO_2 eq per ton of crude palm oil (CPO) compared to fossil fuel-based boilers [68].

Considering the points discussed above and the potential feasibility of palm fiber as a biomass fuel for boiler systems, it is essential for the government to implement supportive policies. The government can provide Feed-in Tarif (FIT) for biomass-based renewable energy production. This approach follows the example in Malaysia has proposed the introduction of the Feed-in Tariff (FiT) from USD 0.09 kW/h onwards for biomass-based renewable energy production. This scheme offers financial funding up to 500 MUSD and is applicable to both the producer and user of green technology with the expectation that it will benefit more than 140 companies in Malaysia [69]. The government could provide direct subsidies covering 10–15% of capex for the procurement and installation of biomass boilers, in Malaysia , the profitability analysis achieved about USD 14 million of NPV and 56% of IRR with the lowest payback period of 3 years [70]. These policies also should financing schemes for the installation of biomass dryers and boilers in the food industry adopting circular economy principles, particularly the use of palm biomass waste as boiler fuel.

Conclusions

Palm fiber shows strong potential as a sustainable biomass fuel to enhance energy efficiency in the margarine industry, with a calorific value of 17.2 MJ/kg, 47.9% cellulose content, and low ash and moisture levels, it is technically suitable for industrial boilers. Compared to fossil fuels, its use can reduce CO_2, SO_x, and NO_x emissions, and provide cost savings of up to 40% with a payback period under five years. Its abundance as a byproduct in palm oil producing regions, combined with simple integration and alignment with circular economy principles, supports its broader application. With appropriate technologies and policy support, palm fiber can become a strategic and scalable energy solution in the palm oil based food sector Future work should address long-term technical concerns such as potential ash-related corrosion in boiler systems. This study also contributes to SDG 7 on clean energy, SDG 12 on sustainable production, and SDG 13 on climate action through the promotion of renewable biomass in food manufacturing.

Acknowledgements

The authors would like to express their sincere gratitude to the Department of Chemical Engineering, Universitas Negeri Semarang, for the support and academic resources provided during the preparation of this article. Special thanks are also extended to all individuals who contributed to constructive discussions and data provision that enriched the quality of this review.

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