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Research article

Potential exportation of wood pellets and torrefied biomass pellets logistics cost analysis: A comparative case study from Portugal

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Abstract: This study evaluates the logistics cost associated with transporting Wood Pellets (WP) and Torrefied Biomass Pellets (TBP) from Aveiro, Portugal's principal WP exporting port, to Northern European destinations. With increasing emphasis on sustainable energy, understanding the cost dynamics between WP and TBP becomes crucial for market competitiveness. Using data sourced from the Argus Biomass Markets report, we compared the energy in gigajoules per ton of both WP and TBP. Torrefaction results in pellets with superior energy and bulk densities, influencing their transportation logistics costs. The main metrics for comparison were cost per energy unit and the implications of energy and bulk densities on transport costs. Preliminary findings indicate that although torrefied pellets undergo more significant mass loss than energy loss, their enhanced energy and bulk densities present logistical advantages. These advantages manifest as more tons per volume unit and heightened energy per ton, which ultimately lead to reduced transportation cost per energy unit. The insights from this analysis provide valuable input for the biofuel sector. By understanding the cost benefits associated with TBP transportation in contrast to WP, stakeholders can make strategic decisions, bolstering the competitiveness of Portuguese biofuel products in the European domain.

Keywords: torrefied biomass pellets; torrefaction; wood pellets; energy costs; biomass energy

1. Introduction

The conservation of the environment has emerged as a crucial concern for global communities in recent decades, prompted by the adverse effects of human actions on the natural world and its subsequent responses [1]. The concentration of greenhouse gases has steadily increased over the past century, leading to a rise in global temperatures, which can be attributed, in part, to human activities that emit these gases [2,3]. Heightened awareness of the finite nature of natural resources has underscored the need to preserve them, as their non-preservation poses a serious threat to the well-being of future generations. In developed nations, energy technologies have coalesced to address the challenges stemming from the widespread usage of oil and the increasing global apprehension regarding the growing concentration of carbon dioxide (CO_2) in the Earth's atmosphere [4]. The strategic implications of alternative energy sources ought to be contemplated, given that a substantial proportion of the world's oil reserves are situated in regions that are embroiled in political and ethnic conflicts that are unlikely to be resolved in the near future [5].

Portugal's objective is to generate 60% of its electricity from renewable sources by 2020 and to fulfill 31% of its final energy consumption from renewables by the same year [6]. In addition, Portugal intends to decrease its reliance on fossil fuels and imports of such energy sources [7]. The pursuit of alternative sources for thermal energy production that have minimal environmental impact implies that biomass energy is likely to assume a critical role when compared to other forms of renewable energy [8]. Biomass has been a fundamental energy resource since ancient times, with people using leaves, wood, and waste in their daily lives [9]. While fossil fuels have largely supplanted biomass since the industrial revolution, biomass is now gradually regaining acceptance as a valuable energy option [10]. The energy derived from biomass is an interesting and unique source as it is easily obtainable globally and renewable, unlike fossil fuels that are geographically restricted [11]. As a result, biomass has the potential to play a significant role in the energy mix of all continents [12]. However, raw biomass faces several challenges in competing with fossil fuels due to its physical properties [13]. Nevertheless, pre-treatment of solid biomass can improve its competitiveness [14]. According to data from the Spanish Association for the Energetic Enhancement of Biomass (AVEBIOM), the use of biomass, particularly pellets, for heating can lead to savings of around 50% in fuel costs [15]. Biomass plays a crucial role in the production of thermal energy, with most of it obtained from forests and forestry operations processed into wood chips after tree felling [16].

In recent years, numerous companies have continued to invest in wood pellet (WP) plants for the production of heat and electricity, resulting in global production of 28.3 million tons in 2018 [17]. By 2019, the global production capacity of wood pellets had increased by 9%, reaching 30.9 million tons [18]. Modern uses of wood pellets continued to increase, with a significant rise in the use of biomass for district heating in Baltic and Eastern European regions [19]. The use of biomass electricity has also grown steadily, particularly in China, Japan, Germany, and the United Kingdom [20]. As of 2019, the European Union remained the largest wood pellet supplier and producer, with Germany, Sweden, Latvia, and Portugal among the top producers [21]. Portugal mainly produces wood pellets for export, with its production increasing since 2008, exporting almost all its pellets to the United Kingdom, Netherlands, Belgium, and Denmark [22].

Torrefaction is a promising process used to produce high-grade solid biofuels from various streams of woody biomass or agroresidues [23]. The process results in a stable, homogeneous, high-quality biofuel with a far greater energy density and calorific value than the original feedstock, providing significant benefits in some logistics activities such as handling and storage, as well as opening up a wide range of potential uses [24,25]. Compared to untreated biomass, torrefied biomass has several benefits, such as higher calorific value, more homogeneous product, higher bulk density, increased grindability, durability, a hydrophobic nature, and increased resistance to biological activity [26]. This results in a high-grade biofuel that can be used as a replacement fuel for coal in electricity and heat generation and as a raw material for gasification processes in the production of high-value bio-based fuels and chemicals [26,27].

Torrefaction has gained significant interest in the bioenergy industry due to its potential benefits, including improved handling, milling, and co-firing capabilities [28]. Major European power producers have tested and reported successful utilization of torrefied biomass in coal-fired power plants, and several studies and publications have highlighted the feasibility of using existing handling and storage facilities for torrefied biomass [29]. Moreover, research has suggested that the supply chain for fuel pellets made from torrefied biomass is more cost-efficient compared to conventional wood pellets [30]. The benefits of torrefied biomass in reducing logistics costs for bioenergy chains have been highlighted in several studies and publications, making torrefaction a promising pre-treatment method for the bioenergy industry [31]. These findings suggest that torrefied biomass may offer a more cost-effective and efficient solution for the bioenergy industry, and further research is necessary to analyze the full potential of torrefaction in reducing logistics costs for bioenergy supply chains [32,33].

The logistics costs associated with energy products exhibit significant variability based on numerous factors, including the nature of the product, the distance covered during transportation, the mode of transportation utilized, and regulatory standards established by the government [34]. Various logistics expenses can impact energy products, such as transportation costs, which comprise fuel expenses, driver compensation, freight fees, and vehicle maintenance costs [35]. Certain energy products may necessitate transportation in specialized tanker ships, which can incur greater costs than land-based transportation [36]. Storage expenses, conversely, hinge upon the duration required for storage before delivery to the consumer, and energy products like oil and natural gas are commonly stored in tanks or reservoirs [37]. Regulatory costs, such as government levies and taxes associated with energy production and transportation, may also elevate logistics expenses. Specific regulations related to the production and transportation of certain energy products can exist within particular countries [38,39]. Ultimately, safety costs are also a significant consideration, encompassing protective measures for employees, facilities, and communities where energy products are manufactured and transported [40]. The transportation of energy products via pipelines, for instance, may necessitate additional measures to prevent leaks or explosions [41].

Logistical concerns play an increasingly pivotal role in the domain of biomass-derived fuels [42]. Biomass represents a renewable energy source that has experienced significant growth in recent decades [43]. However, the production, storage, and transportation of biomass entail a range of logistical challenges that must be carefully considered [44]. Production of biomass may take place in rural areas, situated at a considerable distance from urban centers, resulting in elevated transportation and storage expenses [45]. The nature and density of biomass can differ markedly, thereby influencing the optimal choice of transportation mode [46]. Storage of biomass also presents a unique challenge, as moisture and mass loss can occur over time [47]. Consequently, the choice of the most suitable storage system can significantly affect logistical costs [48]. Transportation of biomass may be more intricate than that of conventional fossil fuels, owing to the greater volume and distinctive characteristics of biomass [49]. Accordingly, selection of the most efficient and secure mode of transportation is critical to minimizing logistical costs and ensuring product delivery in optimal condition [50]. Logistical issues are integral to the success of biomass-derived fuels and necessitate appropriate attention to ensure the economic and environmental sustainability of this form of renewable energy [51].

The transportation of wood pellets over long distances, especially by sea, incurs significant costs, underscoring the crucial importance of optimizing transportation through increasing energy density [52]. Wood pellets are a form of biomass that has gained widespread attention as a renewable energy source, with increasing demand for their use in power generation, heating, and other applications [53]. However, transportation costs can represent a significant portion of the overall costs of wood pellets, particularly when shipping to distant markets [54]. One approach to mitigate the impact of transportation costs is to optimize the energy density of wood pellets [55]. By increasing the energy content of each pellet, a higher volume of energy can be transported per unit weight, resulting in more efficient and cost-effective transportation [56]. This can be achieved through various means, such as by compressing the pellets to increase their density or by improving the quality of the raw material used to produce them [57]. Therefore, it is clear that optimization of the transportation of wood pellets through increasing their energy density is of paramount importance for achieving cost-effective and sustainable use of this renewable energy source [58].

In fact, effective management of logistics costs has emerged as a core determinant of overall efficiency and sustainability. Starting off with a focus on the reduction of carbon emissions, studies have increasingly turned their attention to multi-stage smart production for biofuels. This is crucial given the ever-growing demands for cleaner energy and the global agenda towards achieving sustainable development goals. Rane and Thakker [59] elaborated on a unique model that integrates IoT-based mechanisms within production stages to ensure reduced carbon footprints. Their methodology emphasizes the multi-staged nature of biofuel production, where raw materials undergo various transformation processes. Linking this to Varjani et al. [60] findings, there is a clear alignment in the emphasis on process integration to mitigate carbon emissions. Upon this, a subsequent stream of research concentrates on creating an efficient sustainable approach to biofuel production, giving precedence to environmental and energy aspects. In this context, Moro and Helmers [61] proposed a hybrid approach that integrates solar energy into the biofuel production process. This innovation, while reducing the dependence on conventional energy sources, also aids in slashing logistics costs associated with energy procurement.

The interconnected relationship between biofuel production quality improvement and carbon emissions has begun to shape smart, sustainable supply chain management models. Darvish et al. [62] presented an intricate model showcasing the trade-offs between quality improvements and emissions. Their research harmoniously connects with Nunes et al. [63] findings which highlight that investments in quality do not just lead to superior biofuels but also significantly diminish logistics-associated costs and carbon footprints. With a nod to economically independent reverse logistics, there is a distinct branch of research that encapsulates customer-centric closed-loop supply chains specifically for herbal medicines and biofuel. This becomes significant, as Tabor et al. [64] put it, due to the unique challenges and opportunities herbal resources present. By leveraging these resources, there is potential to create an efficient loop, ensuring minimal wastage and maximum value extraction, hence ensuring a cost-effective mechanism.

On the front of sustainable smart multi-type biofuel manufacturing, the focus sharply turns to optimum energy utilization under flexible production. Clomburg et al. [64] exploration into this area showed that diversified biofuel production methodologies, when orchestrated smartly, cannot just be flexible but also massively energy-efficient. This has a ripple effect on logistics costs, given the reduced need for energy and resource shuttling across stages. Subsidies have always played a critical role in agriculture and related industries. For growers and biofuels-plants in the closed-loop supply chain of herbs and herbal medicines, a cost-effective subsidy policy is of paramount importance. Garai et al. [65] approached this with a novel bi-objective optimization in T-environment. Their findings suggest that when subsidy distribution is optimized using real-time data and forecasts, it leads to a more efficient supply chain, effectively trimming logistics costs. Lastly, the question of waste and energy consumption in a multi-stage smart sustainable biofuel production system is one that dovetails the entirety of the aforementioned research streams. In this avenue, Sarkar and Sarkar [66] presented a comprehensive study which when compared to our current discussion, essentially wraps it all up. Their findings revolve around the need for a holistic approach. They argue that every stage, from procurement to production to distribution, needs smart interventions to cut down waste and energy consumption, thereby reflecting positively on logistics cost parameters.

The objective of this study is to perform a comparative analysis of the logistics costs associated with the purchase of Wood Pellets (WP) and Torrefied Biomass Pellets (TBP) produced in Portugal and exported to the main consumer markets in Northern Europe, namely Belgium, England, Denmark, and Sweden. The study seeks to evaluate the transportation costs, handling costs, and storage costs involved in the supply chain of these two types of solid biofuels. The analysis will consider the incoterm FOB (Free on Board) Aveiro port (Portugal) as the starting point for both WP and TBP. The costs related to loading, transportation, and unloading will be calculated for each type of fuel, considering the shipping route and the specific characteristics of each transport mode. The handling and storage costs associated with the reception of the product at the destination ports will also be taken into account. The results of this study will provide insights into the total cost of each type of fuel and will allow for a comparison of the advantages and disadvantages of each option from a logistics standpoint. This information can be useful for biomass suppliers, end-users, and policy-makers to make informed decisions regarding the most cost-effective and sustainable way to transport solid biofuels from Portugal to Northern European markets.

2. Materials and methods

This study has gathered data on the prices of Wood Pellets (WP) and Torrefied Biomass Pellets (TBP) from major domestic WP producers in Portugal with experience in exporting to northern European countries such as England, Belgium, Denmark, and Sweden. However, due to limited production capacity, only one TBP producer is currently active in Portugal with very limited export capacity. In addition, the study has consulted with shipping companies experienced in pellet transportation to gain an understanding of the logistics operations involved in exporting WP. The superior hydrophobic properties of TBP are assumed to provide an advantage in storage. The transportation costs from the port of Aveiro to the main ports of northern Europe were obtained from the Argus Biomass Markets Report and compared to information provided by exporting companies.

The port of Aveiro is the primary exporting port of WP from Portugal to northern European countries, with several storage and handling infrastructures. Is located on the western coast of Portugal at the outlet of Ria de Aveiro and is divided into five specialized port zones: the North Terminal of the Commercial Sector, the Chemicals Terminal, the Offshore Fishing Sector, the South Terminal of the

Commercial Sector, and the Coastal Fishing Sector. The port primarily handles exports of general cargo, paper pulp, and liquid chemicals, while grain, metal products, and cement are the main imports. Annually, approximately 1,065 vessels and 3,350,000 tons of cargo are handled by the port. The load line zone presents a maximum vessel size of LOA 150 m and draught of 9.0 m.

Argus Biomass is a service offered by Argus Media, a company specialized in market intelligence, data analysis, and commodity pricing. The Argus Biomass service provides information and analysis on the biomass market, including data on prices, supply and demand, production capacity, regulatory developments, and technological innovations. It is used by companies and investors involved in the biomass market, such as producers, traders, distributors, equipment and service providers, investors, and governments. The information provided by Argus Biomass enables clients to make more informed and strategic business decisions regarding the biomass market. The analysis presented here used the information provided by the report released on January 4, 2023 (available at https://www.argusmedia.com/pt/bioenergy/argus-biomass-markets, accessed on February 12, 2023), where reference FOB prices were collected for the port of Aveiro and the freight costs from the port of Aveiro to the ARA ports. These ports are one of the largest centers for logistics and maritime trade in the world, serving a wide range of sectors such as oil, natural gas, chemicals, metals, grains, and other products. The ARA ports are considered a gateway to Europe, allowing for the import and export of goods to various countries around the world. Due to their strategic location and modern and efficient facilities, the ARA ports play a crucial role in international trade and the global economy.

3. The current situation in Portugal

As a result of Portugal's focus on energy efficiency, a national action plan for energy efficiency was created, outlining goals and measures to be taken in various sectors, including industry, buildings, and transportation [67]. The plan includes initiatives to increase energy efficiency in buildings, such as promoting the use of energy-efficient materials and equipment, improving building insulation, and encouraging the use of renewable energy sources like biomass [68]. The government also implemented various policies and incentives to support the development of the biomass sector [69]. For example, a feed-in tariff system was established to support the production of electricity from renewable sources, including biomass [70]. In addition, the government has supported research and development efforts in the field of biomass, with a focus on developing new technologies and improving the efficiency of existing ones [71]. Furthermore, the country's forest resources have also been utilized for the production of biomass [6]. Portugal's forests cover around 35% of the country's total land area, and the government has encouraged sustainable forest management practices to ensure the long-term availability of biomass resources [72]. Forest residues, such as branches and sawdust, are commonly used as biomass feedstocks in Portugal [73]. Portugal's emphasis on energy efficiency and support for biomass energy has led to significant developments in the sector [74]. The country has made strides in increasing the use of biomass for electricity production, reducing emissions, and promoting sustainable forest management practices [75]. The predominance of private forest ownership in mainland Portugal, comprising 84.2% of the total forest area, has led to significant investments in biomass energy in the country [76]. Industrial enterprises own 6.5% of the forest area, while public areas make up the remaining 15.8%, with only 2% belonging to the state's private domain [77]. This is the lowest percentage of public forest ownership in Europe [78]. To leverage its forest resources, Portugal has implemented policies and initiatives to promote the development of the bioenergy sector [79].

Portugal has a significant potential for exporting wood pellets as it is a major producer of this type of biomass, as presented in Figure 1 [80]. The country has vast areas of forest and is also home to a large number of sawmills and other wood processing industries, which generate significant amounts of wood waste that can be used as feedstock for the production of wood pellets [81]. In recent years, Portugal has been increasing its production of wood pellets, with a focus on exporting to other European countries, particularly to the United Kingdom and Italy [82]. The country benefits from its strategic location and good infrastructure, with several ports that allow for efficient transportation of wood pellets to other parts of Europe [83]. Portugal has been investing in developing sustainable forestry practices and promoting the use of renewable energy sources, including biomass [26]. This creates a favorable environment for the growth of the wood pellet industry, both in terms of production and export potential [84]. Portugal's significant production capacity, good infrastructure, and commitment to sustainable forestry practices and renewable energy make it a promising player in the global wood pellet market, with high potential for export growth [85].

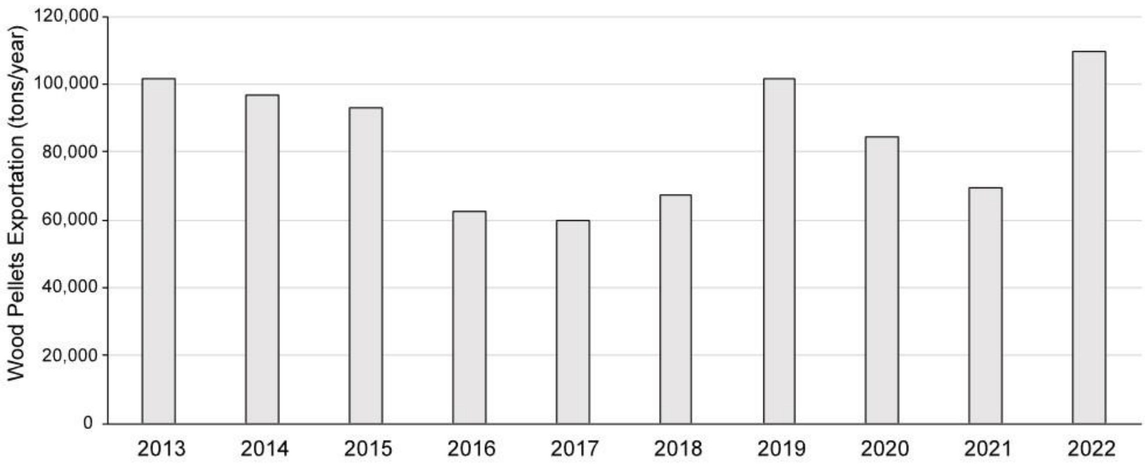

Figure 1. Portugal's wood pellets exportation evolution over the past recent years (data available at https://www.pordata.pt/db/portugal/ambiente+de+consulta/tabela, accessed on September 17, 2023).

Recently in Portugal, torrefied biomass has also received some investments [15]. Torrefaction is a process that converts biomass into a product that has similar properties to coal, such as high energy density and water resistance [86]. This makes torrefied biomass an attractive alternative to coal, especially for power generation and other industrial processes [87]. Several companies in Portugal have started investing in torrefied biomass production, with a focus on export markets [88]. The country benefits from its large forest resources, which provide a steady supply of biomass, and its strategic location, which allows for efficient transportation to other European countries [6]. Torrefaction is a relatively new technology, and Portugal has been investing in research and development to improve the efficiency and sustainability of the process [89]. This creates opportunities for Portuguese companies to become leaders in this emerging industry. The investment in torrefied biomass production in Portugal is a promising development that could contribute to the growth of the country's renewable energy sector and its export potential [90].

4. Results and discussion

This study assumes that buyers of Torrefied Biomass Pellets (TBP) will pay the same base price per gigajoule (GJ) as they would for Wood Pellets (WP). Using an assumed price of 308.34 € per metric ton and the incoterm Free on Board (FOB) Aveiro port in Portugal for WP, a value of 19.27 €/GJ FOB is obtained based on the energy densities presented in Table 1. This value is consistent with the reference values found in literature and technical reports analyzing the emerging TBP market. However, the study acknowledges that TBP buyers may not initially be willing to pay more than they usually do for WP until they fully comprehend the benefits of TBP, such as higher grindability, hydrophobicity, and energy density. Therefore, it is important for TBP suppliers to educate potential buyers about these advantages and provide evidence of cost savings in the long run. The study also highlights the need for further research to analyze the potential benefits and drawbacks of using TBP compared to WP, including the effects on the performance of boilers and handling and storage facilities.

In the transportation of WP and TBP from the port of Aveiro in Portugal to the main North European ports, the most used vessel size is 2,990 tons, with a volume capacity of approximately 4,750 m^3. It is worth noting that the bulk carrier for both WP and TBP is filled to its maximum volume capacity. Table 1 provides information on the energy content that can be loaded into a 4,750 m^3 bulk carrier for both WP and TBP. Additionally, an average shipping cost of 32 €/t from Aveiro port to ARA ports was estimated for this study. It is important to consider the transportation costs when comparing the logistics costs of WP and TBP. Although TBP has a higher energy density, resulting in lower shipping costs per GJ compared to WP, the cost per energy unit is higher due to the lower energy content that can be loaded into a fully loaded vessel. Hence, the total transportation cost of TBP may be higher than that of WP. The difference in energy content between WP and TBP presented in Table 1 is a significant factor in determining the cost per energy unit. As shown, a fully loaded vessel of TBP can hold 25% more energy compared to WP. Consequently, a fully loaded vessel of TBP has a lower cost per energy unit compared to WP, specifically 1.37 €/GJ for TBP and 2.10 €/GJ for WP. It is noteworthy that the difference in cost per energy unit is expected to increase as the vessel size increases.

Table 1. Energy and bulk densities for WP and TBP and estimated costs for shipping per GJ.

	WP	TBP	Data source
Energy (GJ/t)	16	21	[88,91]
Bulk density (kg/m^3)	600	700	[88,91]
Energy density (GJ/m^3)	9.60	14.70	(1)
Vessel capacity (m^3 and t)	4,740 m^3		(2)
	2,990 t		
Total energy loaded (GJ)	45,504	69,678	(1)
Shipping cost (€/GJ)	2.10	1.37	(2)

*Note: (1) Calculation using acquired data, (2) Information obtained by interviewing logistics operators.

In Table 2, the cost per delivered GJ of each fuel is presented, based on the FOB value of 19.27 €/GJ and the estimated shipping costs. The cost per delivered GJ of WP is 21.35 €, while that of TBP is 18.64 €. It is important to note that the shipping cost per ton of TBP is slightly lower than that of WP due to its higher energy density. However, the cost per energy unit of TBP is still lower, which highlights the potential economic advantages of using TBP over WP in long-distance transportation. It is also important to consider that buyers may initially be hesitant to pay a higher price for TBP compared to WP. However, once they become more familiar with the benefits of TBP, such as its higher grindability, hydrophobicity, and energy density, they may be more willing to pay a higher price. Therefore, it is crucial to continue to conduct research and educate buyers on the potential advantages of TBP to encourage its wider adoption in the market.

Table 2. Cost per GJ in destination.

	WP	TBP
Aveiro FOB total price	875,862 €	1,203,339 €
Cost of shipping	95,680 €	
Total price at buyer's port	971,542 €	1,299,019 €
Cost per GJ for the buyer	21.35 €/GJ	18.64 €/GJ

In a first analysis, Table 2 provides a comparison of the FOB prices of WP and TBP at the Aveiro port in Portugal, as well as the corresponding cost per delivered GJ of each fuel. The table highlights that the cost of a fully loaded vessel of TBP is slightly lower than that of WP, primarily due to its higher energy density, which results in a lower shipping cost per GJ. However, the higher energy content of TBP leads to a reduced energy loading capacity in a fully loaded vessel, ultimately resulting in a higher cost per energy unit for TBP compared to WP. It is noteworthy that the cost per delivered GJ of TBP is 18.54 €, which is marginally lower than the cost per delivered GJ of WP, which is 21.35 €. These findings suggest that TBP can be a viable alternative to WP, particularly for long-distance transportation, despite being a more expensive pre-treatment process. While the higher cost of TBP is offset by the lower logistics costs, further research is necessary to analyze other costs or benefits associated with the properties of each fuel type. It is imperative to consider factors such as hydrophobicity and grindability to provide a more comprehensive analysis and include these costs and benefits in the purchasing value of the products.

The first point of comparison between WP and TBP lies in their inherent energy densities. TBP possesses a 25% higher energy density compared to WP, as evidenced by their respective energy densities of 21 and 16 GJ/t. This greater energy density translates to higher grindability, hydrophobicity, and overall better combustion characteristics. For energy producers, this could result in more efficient combustion processes, potentially reducing operational costs over the long run. However, when evaluating the overall economics, especially in the context of transportation, complexities arise. WP and TBP transportation from the port of Aveiro in Portugal to North European ports, primarily utilizes vessels with a 2,990-ton capacity. While TBP, with its higher energy density, has the advantage of lower shipping costs per GJ, it presents a paradox. Its denser nature means a fully loaded vessel will carry less energy overall compared to WP. This is evident from Table 1 where a fully loaded vessel of TBP holds 69,678 GJ of energy as opposed to the 45,504 GJ for WP. Thus, while TBP can be cheaper per GJ to ship, a fully loaded vessel might end up costing more due to the lesser amount of energy it can transport.

Another aspect that deserves further consideration is the market perception and adoption rate of TBP. Given its relatively early presence in the market, TBP suppliers may face initial reluctance from potential buyers, especially if they are unfamiliar with TBP's benefits. This situation is akin to the challenges new technologies face when they first enter a market dominated by a more established alternative [92]. As a result, TBP's true value might not be readily apparent until its unique benefits, such as higher grindability, hydrophobicity, and energy density, are fully understood and appreciated by potential buyers.

Delving deeper into the financial analysis using Table 2, we observe a nuanced picture. While the FOB total price for TBP at Aveiro port is higher than WP (1,203,339 € vs. 875,862 €), the cost per GJ for the buyer is indeed lower for TBP at 18.64 €/GJ, compared to WP's 21.35 €/GJ. This reinforces the idea that while the upfront cost for TBP might be higher, the per unit energy cost can be lower, possibly translating to long-term savings for end-users, especially in scenarios involving long-distance transportation. Also, while TBP has shown potential advantages over WP in specific contexts, there remains a need for comprehensive research into various other factors that could influence the choice between the two. Aspects like the hydrophobic nature of TBP, which reduces susceptibility to moisture, and its grindability, which could affect boiler performance and wear, are crucial. Both these factors could introduce additional costs or savings that need to be incorporated in any financial analysis.

5. Conclusions

TBP have been scrutinized in relation to WP for their cost efficiency and other attributes. Delving into the specifics, this study works under the premise that TBP will be priced the same per GJ as WP. Based on an energy density derived from Table 1 and the assumed price of 308.34 € per metric ton for WP at the FOB Aveiro port in Portugal, a value of 19.27 €/GJ FOB is achieved. This figure resonates with reference values in literature that review the budding TBP market. When it comes to transportation, especially from Aveiro port to North European ports, 2,990-ton vessels are typically used. These vessels have a volume capacity of roughly 4,750 m^3 and are filled to their maximum volume capacity for both WP and TBP transport. The study's estimated average shipping cost stands at 32 €/t for routes between Aveiro port and ARA ports. A striking difference is found in the energy content between TBP and WP, with a fully loaded TBP vessel holding 25% more energy, leading to a cost per GJ of 1.37 € for TBP and 2.10 € for WP. It is evident from the results that the cost for a fully loaded vessel of TBP is nominally lower than WP, owing to its superior energy density which translates to reduced shipping costs per GJ. Yet, TBP's heightened energy content implies a lower energy loading capacity in a full vessel, making its cost per energy unit slightly higher than WP. Specifically, TBP's cost per delivered GJ stands at 18.54 €, a tad lower than WP's 21.35 €. This comparative analysis highlights that TBP could be a feasible substitute to WP, especially in the context of long-haul transportation. This is even more plausible when considering TBP's superior grindability, hydrophobicity, and energy density. The upshot is, while TBP is pricier as a pre-treatment process, it is balanced out by reduced logistics expenses. For a rounded perspective, future studies should focus on evaluating other factors like hydrophobicity and grindability, and subsequently incorporate these attributes into the final purchasing value.

Use of AI tools declaration

The author declares he has not used Artificial Intelligence (AI) tools in the creation of this article.

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Conflict of interest

The author declares no conflict of interest.

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