Challenges and adaptation strategies for Vietnam's wood export industry in the face of EU carbon border regulations

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Abstract:

Vietnam's wood export industry, while crucial to the national economy, faces significant challenges from the European Union's Carbon Border Adjustment Mechanism (CBAM). With small and medium enterprises (SMEs) comprising 90% of the sector, the industry must address high carbon emissions, external market dependence, and evolving environmental regulations to maintain competitiveness. This research analyses CBAM's impact on Vietnam's wood industry and identifies effective adaptation strategies under new environmental standards. Using an inductive theory-building approach, the study integrates economic theories on carbon pricing and international trade with empirical assessments of production emissions. Findings reveal the sector's current emissions of 220-280 kg CO_2e per cubic meter, highlighting the urgent need for technological innovation and sustainable practices. The research identifies key adaptation strategies: implementing heat pump kilns that reduce emissions by 45%, developing blockchain-based supply chain traceability, diversifying markets, and strengthening EU partnerships. These measures support the industry's commitment to reduce emissions by 45% by 2030 compared to 2020 levels. Recommendations focus on three pillars: technology adoption through cooperative frameworks for resource-limited SMEs, market diversification, and enhanced policy support for green transitions. The study contributes to understanding how developing economies' traditional industries can adapt to evolving global environmental standards while maintaining economic viability. The findings underline the importance of proactive adaptation to international environmental regulations for sustaining economic viability in developing economies. By adopting innovative technologies and diversifying markets, Vietnam's wood export industry can mitigate the adverse impacts of CBAM, ensuring long-term competitiveness and contributing to global sustainability goals.

Keywords: **carbon border adjustment mechanism, carbon emissions, small and medium enterprises, sustainability, Vietnamese wood exports.**

Classification numbers: **2.1, 2.2, 2.3**

1. Introduction

Vietnam's wood export industry has emerged as a significant contributor to the country's economy, establishing itself as one of the world's leading exporters of wood and wood products. With its rich forest resources and skilled labour force, Vietnam has capitalised on the growing global demand for furniture and other wood-based goods. In 2021, Vietnam's wood and wood product exports reached $14.8 billion, accounting for 4% of the country's GDP and marking a 19.7% increase from the previous year. However, the industry faced challenges in 2023, with exports declining to $13.4 billion [1].

The European Union (EU) has long been one of Vietnam's key markets for wood exports. From 2018 to 2022, Vietnam's wood exports to the EU-27 showed a general upward trend, with some fluctuations. In this context, the EU-Vietnam Free Trade Agreement (EVFTA), which came into effect on 1 August 2020, presents both opportunities and challenges for the industry [2].

The EVFTA, with its commitment to strong market opening and the elimination of import duties on nearly 100% of the EU's tariff lines, has opened up significant opportunities and prospects for Vietnamese wood export businesses [3]. This agreement allows companies to boost exports, diversify their product structure, and enhance the competitiveness and value of export products entering the EU market.

However, the wood export industry now faces a substantial challenge from an unexpected quarter: environmental regulations in one of its key markets. The European Union, long at the forefront of climate change mitigation efforts, is poised to implement a groundbreaking policy known as the CBAM [1]. This mechanism aims to level the playing field between EU producers subject to stringent carbon pricing and their international competitors operating under less restrictive environmental regimes [4, 5].

While CBAM directly targets sectors such as cement, iron and steel, aluminium, fertilisers, hydrogen, and electricity, it indirectly affects the wood industry [6]. The industry is closely linked to industrial production, and wood processing facilities consuming over 1,000 tons of oil equivalent (TOE) annually may be subject to greenhouse gas inventories and emission quotas [7, 8].

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For Vietnam's wood export industry, which relies heavily on energy-intensive processes and has a significant carbon footprint, the advent of CBAM presents a formidable challenge [9]. This policy threatens to erode the competitive advantage that Vietnamese wood products have long enjoyed in the European market, potentially disrupting established trade patterns and economic relationships [10].

The urgency of this situation is highlighted by industry leaders like Nguyen Liem, Chairman of the Binh Duong Wood Processing Association (BIFA), who emphasises that adapting to these new environmental standards is a matter of survival for the wood industry. The loss of orders in the textile industry to competitors like Bangladesh due to slow green transformation serves as a cautionary tale for wood exporters [11]. Therefore, this paper examines the impact of the EU's CBAM on Vietnam's wood export industry and explores the urgent need for adaptation strategies.

This research is motivated by the need to understand how CBAM, a significant regulatory shift, affects Vietnam's wood export industry and to identify effective adaptation strategies. By using an inductive theory-building approach, this study aims to provide new insights into the practical applications of carbon pricing and its implications for international trade. The research contributes to the existing body of knowledge by highlighting the specific challenges faced by a key export industry in a developing economy and proposing actionable strategies to mitigate these challenges.

The study argues that while CBAM poses significant challenges, it also presents an opportunity for the industry to innovate, improve sustainability practices, and ultimately strengthen its position in the global market [12, 13]. By analysing the current landscape, potential impacts, and possible responses, this study aims to provide insights that can guide both industry stakeholders and policymakers in navigating this complex and evolving situation.

The subsequent sections will delve into the theoretical framework underpinning carbon pricing and trade, review relevant literature, assess the current state of Vietnam's wood export industry, and propose strategies for adapting to the new regulatory environment. Through this comprehensive analysis, the article seeks to contribute to the ongoing dialogue on sustainable trade and offer practical recommendations for maintaining the competitiveness of Vietnam's wood export sector in an increasingly carbon-conscious global economy [14].

2. Theoretical framework

2.1. Carbon pricing and international trade

Carbon pricing is one of the most widely recognized market-based mechanisms to mitigate climate change, grounded in the Pigovian tax concept introduced by economist A.C. Pigou (1920) [15]. A Pigovian tax corrects the negative externalities caused by activities like greenhouse gas emissions, which cause social and environmental harm that is not reflected in the price of goods. Carbon pricing can take two primary forms: carbon taxes and cap-and-trade systems (or emissions trading schemes, ETS).

Carbon tax: This approach assigns a fixed price per ton of CO_2 emissions, increasing the cost of carbon-intensive goods and services. A carbon tax creates a direct economic disincentive for carbon emissions, encouraging producers to seek out more energy-efficient or less carbon-intensive methods of production [16].

Emissions trading system (ETS): Also known as "cap and trade", this system establishes a limit (cap) on total carbon emissions allowed within an economy or industry. Companies receive or buy emissions permits, which they can trade among themselves. The market-driven pricing of these permits creates a flexible mechanism to reduce emissions where it is cheapest [17].

Carbon pricing in the context of international trade introduces the concept of carbon leakage, where industries relocate their production to countries with less stringent climate policies to avoid carbon costs [4]. This has been a significant concern for the EU, as European producers subject to internal carbon pricing face higher production costs compared to international competitors. The CBAM is designed to address carbon leakage by imposing tariffs on imported goods based on their carbon content, ensuring that EU producers are not disadvantaged in global competition [6].

Research by F. Branger, et al. (2014) [5] shows that carbon leakage can be mitigated by such border adjustments, as they level the playing field between domestic and foreign producers. CBAM functions as a protective measure for the EU's carbon pricing policies, ensuring that imported goods face similar environmental costs as those produced within the EU.

For Vietnam's wood export industry, CBAM could impose significant additional costs. Wood processing, especially in energy-intensive stages like drying and sawing, is carbon-intensive, potentially subjecting Vietnamese wood products to CBAM-related tariffs when entering the EU market [18]. This makes carbon pricing a critical factor in shaping trade competitiveness, forcing industries to innovate and reduce emissions or risk losing market share due to higher costs.

2.2. Environmental regulations and competitiveness

The relationship between environmental regulations and industrial competitiveness is complex and has been extensively discussed in economic theory. The Porter Hypothesis, proposed by economist M.E. Porter (1995) [13], suggests that stringent environmental regulations can stimulate innovation, leading to improved efficiency and competitiveness. Porter argued that well-designed regulations incentivise firms to innovate in ways that not only meet regulatory requirements but also improve productivity, thus offsetting the costs of compliance.

However, the pollution haven hypothesis presents a contrasting perspective, suggesting that stringent environmental

regulations may drive industries to relocate to countries with laxer environmental standards, which could lead to a loss of competitiveness in highly regulated regions [10].

Empirical studies provide mixed evidence. A review by S. Ambec, et al. (2013) [12] supports the Porter Hypothesis by showing that firms that innovate in response to environmental regulations can gain a competitive advantage through increased efficiency and product differentiation. Conversely, a study by A.B. Jaffe, et al. (1995) [19] found that environmental regulations tend to increase production costs, leading to short-term losses in competitiveness, especially in industries with high energy consumption.

In the context of Vietnam's wood export industry, the introduction of CBAM and other environmental regulations will likely increase operational costs. Energy-intensive processes such as sawing, kiln drying, and surface treatment are vulnerable to carbon pricing [8]. However, this challenge also presents an opportunity for the industry to invest in cleaner technologies, enhance resource efficiency, and adopt internationally recognized eco-certifications (e.g., FSC or PEFC) [18, 20]. This shift could open up premium markets and foster long-term competitiveness, aligning with the Porter Hypothesis.

2.3. Sustainable supply chain management

Sustainable supply chain management (SSCM) integrates social, environmental, and economic considerations into traditional supply chain operations, aiming to create long-term economic value while minimising environmental impact and ensuring social responsibility. This concept is based on triple bottom line (TBL) theory, introduced by John Elkington in 1994 [12], which posits that businesses must simultaneously prioritise profit, people, and the planet to achieve sustainable growth.

SSCM incorporates several theoretical frameworks, including:

Lifecycle assessment (LCA): LCA evaluates the environmental impact of products throughout their lifecycle, from raw material extraction to production, transportation, use, and disposal. In the wood industry, LCA can help identify stages of the production process with the highest carbon footprint and guide interventions to reduce emissions. Studies highlight the importance of using LCA to improve sustainability in forestry and wood products by assessing and mitigating environmental impacts [8].

Natural resource-based view (NRBV): Developed by Hart (1995) [20], this theory argues that firms can build a competitive advantage by managing natural resources sustainably. Firms that incorporate eco-friendly practices - such as sustainable harvesting, reducing energy use, and adopting renewable resources - can outperform competitors by meeting regulatory demands and consumer expectations for environmental responsibility.

In the wood export sector, SSCM can be applied through the following strategies:

Sustainable sourcing: Ensuring that wood is harvested from forests managed in compliance with sustainable forestry standards, such as those set by the Forest Stewardship Council (FSC) [18]. FSC certification guarantees that wood products come from responsibly managed forests that provide environmental, social, and economic benefits.

Energy efficiency in processing: Wood processing is an energy-intensive industry, particularly in drying, cutting, and shaping wood. Investing in energy-efficient technologies-such as solar-powered kilns or advanced drying systems-can significantly reduce emissions and help the industry comply with CBAM. A report by FAO (2010) [15] emphasises the importance of energy-efficient technologies in improving the sustainability of wood processing.

Supply chain transparency and traceability: Establishing robust systems to track the carbon content of products along the supply chain is crucial for compliance with CBAM [21]. Transparency ensures that every stage of the supply chain, from harvesting to processing, can be verified for its environmental impact. Traceability systems also support the marketing of wood products as eco-friendly, improving consumer trust and marketability.

SSCM also emphasises collaboration across the supply chain. For Vietnam's wood industry, partnerships with European buyers and regulatory bodies can help meet CBAM requirements more effectively, while building long-term resilience and sustainability in the face of evolving global environmental standards [8].

3. Literature review

The literature on the impact of carbon pricing on export industries shows that carbon pricing mechanisms can increase costs for producers, especially in energy-intensive sectors like manufacturing and heavy industries. M. Sato, et al. (2016) [17] and R. Martin, et al. (2014) [22] explain that carbon pricing can lead to "carbon leakage," where industries relocate to regions with less stringent environmental regulations to avoid these costs. However, their studies also highlight that such policies often encourage firms to innovate and adopt more energy-efficient technologies, leading to long-term competitiveness. For export industries, carbon pricing presents both risks and opportunities: while higher production costs may hurt competitiveness, companies that innovate to reduce their carbon footprint can gain a competitive edge in environmentally conscious markets.

In the wood industry, lifecycle assessments have revealed that much of the carbon footprint comes from energy-intensive processes like drying, cutting, and transporting wood products. Research by scientists points out that energy use during wood processing is one of the main contributors to greenhouse gas emissions, emphasising the need for cleaner, more energy-efficient technologies [21]. Studies by the FAO also stress the importance of sustainable forestry practices, noting that while

wood itself can be a renewable resource, improper harvesting and processing techniques can undermine its environmental benefits [15]. This highlights the dual focus needed in the wood industry on both upstream (forestry) and downstream (processing) sustainability practices.

Regarding the EU's CBAM, A. Cosbey, et al. (2020) [6] and A. Mattoo, et al. (2012) [10] have explored its potential effects on developing countries. They argue that CBAM could impose significant financial burdens on industries in these regions by increasing the cost of exporting to the EU. These studies point out that without international support for technology transfer and capacity building, many developing countries could struggle to meet the EU's stringent carbon standards. This could lead to a loss of market share, particularly for industries like steel, cement, and potentially wood, where the carbon intensity of production is a key concern. However, Mattoo, et al. also emphasise the potential for CBAM to stimulate global green transitions, suggesting that countries that proactively invest in low-carbon technologies and processes may find new opportunities in environmentally regulated markets.

Successful adaptation strategies in industries targeted by CBAM, such as steel and cement, furniture were analysed to identify transferrable practices for the wood export sector. Those industries have already adapted to stringent environmental regulations offer valuable lessons. For example, the cement and steel industries in Europe have successfully reduced their carbon emissions through technological innovations and energy efficiency improvements, despite initially facing high compliance costs [16]. Similarly, the furniture industry, which is closely related to the wood sector, has adopted sustainable certification schemes (e.g., FSC certification) to meet both regulatory requirements and consumer demand for eco-friendly products [23]. These cases show that while the cost of compliance with environmental regulations can be significant, businesses that adapt by embracing sustainability and innovation often find long-term benefits in improved market access and customer loyalty.

Despite the valuable insights these studies provide, several research gaps remain. There is a noticeable lack of specific studies on the wood industry's response to carbon pricing mechanisms, particularly in Vietnam, where the industry is both economically significant and highly energy-dependent [1]. Most existing research focuses on larger, more energy-intensive industries like steel and cement, leaving the unique challenges of the wood industry underexplored. Additionally, while some studies touch on the role of international support, there is little in-depth analysis of how financial aid, technology transfer, and capacity-building efforts can support industries in developing countries, such as Vietnam's wood export sector, in meeting CBAM requirements.

In the context of Vietnam's wood export industry, these gaps are particularly relevant. The sector contributes significantly to the national economy, with exports reaching $14.8 billion in 2021 [1], but faces challenges from its high carbon footprint due to energy-intensive processes [8]. To address the gap, future research should focus on how Vietnam's wood industry can reduce its carbon emissions through renewable energy adoption, energy-efficient technologies, and sustainable forestry practices [19]. Additionally, studies should explore how international collaborations, particularly with the EU, can facilitate this transition by providing technical assistance and financial support [24]. This would not only help the industry meet the EU's carbon standards but also position Vietnam as a leader in sustainable wood production, ensuring its long-term competitiveness in global markets. Addressing these research gaps is critical for guiding both policymakers and industry stakeholders in developing strategies to align Vietnam's wood export industry with emerging environmental regulations.

Therefore, this study aims to bridge the gap by providing a detailed analysis of the specific challenges and opportunities that Vietnam's wood export industry faces under CBAM. It highlights the potential for technological innovation and sustainable practices to enhance the industry's resilience and competitiveness. By proposing actionable strategies and emphasising the need for international collaboration, the research offers practical guidance for policymakers and industry stakeholders. The study's findings contribute to a deeper understanding of how developing countries can adapt to stringent environmental regulations while maintaining economic viability.

4. Methods

4.1. Data collection

Data were collected from multiple sources, including industry reports, academic research about Vietnamese wood export industry. Lifecycle assessment (LCA) data were gathered to quantify the carbon footprint at various stages of the wood processing chain. Secondary data (existing literature and industry databases) was used. Then, strategic recommendations were developed based on both empirical data and theoretical insights from economic and environmental literature. The recommendations focus on technology adoption, market diversification, and policy support to help the industry adapt to CBAM and enhance its long-term competitiveness.

4.2. Analytical framework

The study's analytical framework integrates economic and environmental theories with a focus on carbon pricing, sustainability, and international trade. The following tools and frameworks were applied:

Lifecycle assessment (LCA): Used to quantify carbon emissions at each stage of the wood production process, including raw material extraction, processing, finishing, and transportation. This provided baseline emission data crucial for evaluating reduction strategies.

Natural resource-based view (NRBV): This framework was applied to assess the competitive advantage of sustainable practices, emphasising resource efficiency, innovation, and eco-certification.

5. Vietnam's wood export industry: Current state and challenges

5.1. Overview of the industry's economic importance

Vietnam's wood processing and export industry has emerged as a cornerstone of the nation's economy, experiencing remarkable growth over the past decade and establishing itself as a global leader in wood product manufacturing and trade. In 2021, the industry reached its peak performance with export revenues of $14.8 billion, representing a significant 19.7% increase from 2020's $12.37 billion [11]. This remarkable achievement positioned Vietnam as the world's fifth-largest wood and wood products exporter and second in Asia, trailing only behind China in regional rankings. The sector's contribution to Vietnam's GDP has been substantial, accounting for approximately 4% in 2021, underlining its crucial role in the country's economic landscape and development strategy [1].

The industry's economic significance extends far beyond export revenues, playing a vital role in employment generation and rural development. As of 2023, the sector directly employs approximately 500,000 workers across 5,400 enterprises, with indirect employment reaching nearly 1.5 million people when including related sectors such as forestry, logistics, and support services [25]. The industry's structure is particularly noteworthy, with small and medium-sized enterprises (SMEs) comprising about 90% of the total businesses, creating a robust economic ecosystem that supports local communities. The sector's supply chain extends across 4,500 communes involved in forest plantation, providing sustainable income sources for millions of Vietnamese households, particularly in rural areas where most wood processing facilities are located [2, 11].

Market diversification has been a key strength of Vietnam's wood export industry, though the United States remains the dominant market. In 2021, U.S.-bound exports reached $8.78 billion, accounting for approximately 59.3% of total wood exports, followed by the European Union ($1.53 billion, 10.3%), Japan ($1.33 billion, 9.0%), and China ($1.27 billion, 8.6%) (Fig. 1) [2, 11]. This market distribution reflects both opportunities and challenges, as strong reliance on the U.S. market has proven beneficial during periods of growth but also exposes the industry to risks during economic downturns. The European Union's position as the second-largest market has become increasingly significant, particularly as Vietnam implements the EVFTA, which has opened new opportunities while also introducing stricter environmental and sustainability requirements [25].

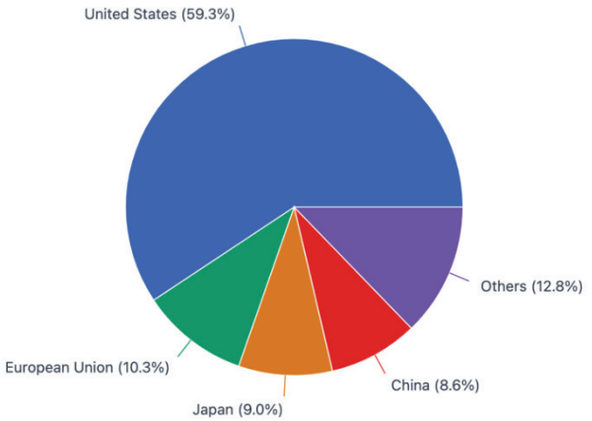

Fig. 1. Vietnam wood export market distribution (2021). Source: Vietnam Timber and Forest Product Association, Ministry of Industry and Trade.

However, the industry faced significant headwinds in recent years, with total export revenue declining to $13.4 billion in 2023, marking a 9.5% decrease from the 2021 peak. This downturn has been attributed to several factors, including global economic challenges, inflation in major markets, and stricter environmental regulations. The implementation of the EU's CBAM and the U.S. Lacey Act amendments have necessitated significant adjustments in production practices and supply chain management [1, 7]. Despite these challenges, the industry has demonstrated resilience through increased investment in technology and sustainable practices, with Vietnamese companies investing an estimated $2.8 billion in modern production facilities and environmental compliance measures between 2019 and 2023 (Fig. 2) [8, 26].

Fig. 2. Vietnam wood export performance (2019-2023). Source: Vietnam Timber and Forest Product Association, Ministry of Industry and Trade.

Looking at the industry's structural composition, large-scale manufacturers account for approximately 10% of enterprises but contribute nearly 70% of total export value [11]. These

companies have been at the forefront of modernisation efforts, with average investment in technology and automation reaching $15-20 million per facility. The industry has also seen significant foreign direct investment (FDI), with accumulated FDI reaching $6.2 billion by 2023, primarily from countries such as Japan, South Korea, and Taiwan [24]. This international investment has not only brought capital but also advanced technology and management practices, contributing to the industry's overall competitiveness.

The wood processing industry's backward linkages have stimulated significant growth in Vietnam's forestry sector, with planted forest area increasing by 200,000 hectares annually. The country now maintains approximately 3.5 million hectares of production forests, providing about 70% of the raw materials needed for the industry [25]. The remaining 30% is imported, with a total import value of raw materials reaching $2.4 billion in 2023, primarily from the United States, New Zealand, and Chile. This combination of domestic and imported resources has enabled Vietnam to maintain its competitive position while working toward greater sustainability and self-sufficiency in raw material supply [11].

5.2. Carbon emissions in the wood production process

The wood production process encompasses multiple stages, each contributing significantly to the industry's overall carbon footprint. Understanding these emissions is crucial for implementing effective reduction strategies and meeting increasingly stringent international environmental standards [8, 15]. A comprehensive analysis of each production stage reveals the complex interplay between manufacturing processes and their environmental impact.

Stage 1: Forest management and raw material extraction:

The carbon emission cycle begins with forest management and logging operations, where the average carbon footprint ranges from 3.8 to 5.2 kg CO_2e per cubic meter of harvested wood [8, 15]. In Vietnam's context, where approximately 70% of raw materials come from domestic forests, the transportation of logs from forest to processing facilities adds an additional 2.1-3.5 kg CO_2e per cubic meter, depending on distance and transport method [11]. Modern harvesting equipment, such as mechanical harvesters and forwarders, typically emit between 0.9-1.2 kg CO_2e per cubic meter of wood harvested. The adoption of reduced impact logging (RIL) techniques in Vietnam has shown potential to reduce these emissions by 30-40%, although only 35% of logging operations currently employ these methods [26].

Stage 2: Primary processing and kiln drying:

The most energy-intensive phase occurs during primary processing, particularly in kiln drying operations. Contemporary wood drying kilns in Vietnam consume between 600-800 kWh of electricity per cubic meter of wood, resulting in emissions of 45-60 kg CO_2e per cubic meter when using grid electricity [26]. Traditional coal-fired kilns, still used in approximately 40% of facilities, generate significantly higher emissions of 85-100 kg CO_2e per cubic meter. The drying process, which typically takes 5-7 days for hardwoods common in Vietnamese production, accounts for roughly 35% of the total energy consumption in wood processing [11]. Recent studies by the Vietnam Timber and Forest Product Association indicate that facilities using modern heat pump kilns have achieved emission reductions of up to 45% compared to conventional methods [11].

Stage 3: Secondary processing and manufacturing:

Secondary processing, including cutting, planing, and shaping, contributes substantially to the carbon footprint. Modern woodworking machinery in Vietnamese facilities consumes an average of 300-400 kWh per cubic meter of processed wood, resulting in emissions of 25-35 kg CO_2e [8]. The manufacturing of engineered wood products, such as plywood and MDF, generates higher emissions due to additional processing requirements and the use of adhesives. Plywood production, for instance, emits approximately 120-150 kg CO_2e per cubic meter, with adhesive application and hot-pressing accounting for 40% of these emissions [5, 14]. Recent investments in energy-efficient equipment by major Vietnamese manufacturers have shown potential for reducing these emissions by 20-25% [8, 19].

Stage 4: Surface treatment and finishing:

The finishing phase, including sanding, coating, and painting, generates both direct emissions from energy consumption and indirect emissions from volatile organic compounds (VOCs). Modern finishing lines consume 150-200 kWh per cubic meter of product, resulting in direct emissions of 12-16 kg CO_2e [8, 26]. VOC emissions from finishing processes average 3.5-4.2 kg per cubic meter of finished product, with associated indirect greenhouse gas impacts. Water-based finishing systems, increasingly adopted by Vietnamese manufacturers, have demonstrated potential to reduce VOC emissions by 60-70% compared to traditional solvent-based systems [27, 28].

Stage 5: Assembly and packaging:

Final assembly and packaging operations contribute relatively lower but still significant emissions. Assembly lines in Vietnamese furniture factories typically consume 100-150 kWh per cubic meter of finished product, generating 8-12 kg CO_2e [8]. Packaging materials, primarily cardboard and plastic, contribute an additional 5-7 kg CO_2e per cubic meter of product. Recent innovations in packaging design and materials have shown potential for reducing packaging-related emissions by 25-30% [29].

Stage 6: Transportation and distribution:

The final stage involves significant emissions from product transportation and distribution. Domestic transportation from factories to ports generates 3-5 kg CO_2e per cubic meter, while international shipping adds 15-25 kg CO_2e per cubic meter for common routes to major markets like the United States and Europe [11]. The implementation of optimised logistics networks and container loading has shown potential for reducing transport-related emissions by 15-20% [8, 26].

Wood waste management and energy recovery:

Wood waste management significantly impacts the overall carbon footprint. Vietnamese wood processing facilities generate approximately 0.3-0.4 cubic meters of wood waste per cubic meter of finished product [8]. When properly utilised in biomass energy systems, this waste can offset 30-40 kg CO_2e per cubic meter of production by replacing fossil fuels. Currently, about 60% of large-scale facilities in Vietnam operate biomass energy systems, while smaller operations often sell wood waste to biomass energy producers [11].

Total life-cycle emissions and reduction initiatives:

The cumulative carbon footprint across the entire production process ranges from 220-280 kg CO_2e per cubic meter of finished wood products, varying significantly based on product type and processing methods [11, 15]. Leading Vietnamese manufacturers have implemented comprehensive carbon reduction programs, achieving total emission reductions of 25-35% through combined technological and operational improvements. These initiatives have required average investments of $2.5-3.5 million per facility but have resulted in annual operating cost savings of 15-20% through improved energy efficiency [8, 26].

Looking ahead, the Vietnamese wood industry has set ambitious targets for carbon reduction, aiming to decrease emissions by 45% by 2030 compared to 2020 levels. This goal aligns with both national environmental commitments and international market requirements, particularly the EU's CBAM [1, 7, 8].

5.3. Current sustainability practices and certifications

Vietnam's wood industry has undergone a significant transformation in its approach to sustainability and environmental certification over the past decade, driven by both international market demands and domestic environmental policies [18, 26]. The implementation of sustainable practices and acquisition of internationally recognised certifications has become increasingly crucial for maintaining market access and competitive advantage in the global wood products trade.

Forest Stewardship Council (FSC) certification has emerged as the cornerstone of sustainable forest management in Vietnam, with certified forest area growing from 157,000 hectares in 2018 to approximately 350,000 hectares by 2023 [18]. This growth represents a compound annual growth rate (CAGR) of 17.4% in certified forest area. The economic impact of FSC certification has been substantial, with certified products commanding a premium of 15-25% in international markets. Among the certified forest areas, 78% are managed by state-owned enterprises, while the remaining 22% are operated by private companies and smallholders [1, 25].

The Vietnam Timber Legality Assurance System (VNTLAS) has played a pivotal role in ensuring timber legality and traceability [21]. As of 2023, 2,847 companies have registered under VNTLAS, representing approximately 65% of all wood processing enterprises in the country. The system has helped reduce illegal timber in the supply chain by an estimated 47% since its implementation in 2019. Companies participating in VNTLAS have reported an average 28% improvement in market access to high-value destinations such as the European Union and United States [1, 25].

The Programme for the Endorsement of Forest Certification (PEFC) has gained traction as an alternative certification scheme, particularly among larger enterprises [20]. By 2023, 156 Vietnamese companies had obtained PEFC Chain of Custody certification, marking a 65% increase from 2020. These certified companies have reported average revenue increases of 23% following certification, primarily due to improved access to environmentally conscious markets [11].

Investment in sustainable practices has varied significantly across the industry. Large-scale manufacturers, representing about 10% of total enterprises, have invested heavily in sustainability initiatives, with average expenditure reaching $2.5-3.5 million per facility on environmental improvements between 2020 and 2023 [8, 26]. These investments have focused on energy-efficient equipment (45% of total investment), waste management systems (30%), and certification compliance (25%). The results have been noteworthy, with certified companies reporting average energy consumption reductions of 27% and waste reduction of 35% compared to pre-certification levels.

Renewable energy adoption in the wood processing sector has shown promising growth, though still limited in scope [23]. By 2023, 215 large and medium-sized facilities had installed solar power systems, with a total capacity of 180 MW, representing approximately 15% of the industry's total energy consumption. Biomass energy systems, utilising wood waste from processing operations, have been implemented in 423 facilities, generating an equivalent of 250 MW of thermal energy and reducing waste disposal costs by an average of 45% [8, 26].

Small and medium-sized enterprises (SMEs) face significant challenges in implementing sustainable practices and obtaining certifications [14]. The average cost of FSC certification for an SME ranges from $15,000 to $25,000, with annual maintenance costs of $5,000-8,000, representing 3-5% of their annual revenue. To address this challenge, the government has implemented support programs, providing

financial assistance to 387 SMEs for certification processes in 2023, with a total investment of $12.5 million [25].

Water management practices have also seen significant improvement, with certified facilities reducing water consumption by an average of 32% through closed-loop systems and water treatment technologies [8]. Investment in water management infrastructure averaged $180,000 per facility among larger manufacturers, with payback periods ranging from 2.5 to 3.5 years through reduced water costs and compliance penalties.

The industry's commitment to sustainability has extended to supply chain management, with 65% of certified companies implementing comprehensive supplier evaluation systems based on environmental criteria [12, 14]. These systems have led to a 40% increase in the use of certified raw materials and a 55% improvement in supply chain transparency. The average cost of implementing such systems ranges from $50,000 to $100,000 per company, with annual operating costs of $15,000-25,000 [8, 26].

Looking ahead, the Vietnam Timber and Forest Product Association has set ambitious targets for 2025, including increasing FSC-certified forest areas to 500,000 hectares, achieving 80% VNTLAS registration among active exporters, and reducing the industry's carbon footprint by 35% compared to 2020 levels [11]. These goals are supported by a government commitment of $150 million in funding for sustainability initiatives over the next three years, focusing on certification support, technology upgrade grants, and training programs [25].

5.4. Discussion

Impact of CBAM on Vietnam's wood export industry: The introduction of the EU's CBAM represents a significant regulatory shift that poses both challenges and opportunities for Vietnam's wood export industry. CBAM aims to mitigate carbon leakage by imposing tariffs on imported goods based on their carbon content, ensuring that EU producers are not disadvantaged by stringent domestic carbon pricing. This regulatory framework could increase the cost of Vietnamese wood products in the EU market, potentially eroding their competitive edge.

Challenges:

- Increased costs: The primary challenge lies in the potential cost increase for Vietnamese wood exports due to the imposed tariffs. The industry, particularly its small and medium-sized enterprises, may struggle to absorb these costs without significant financial strain.

- Compliance: Achieving compliance with CBAM requirements necessitates substantial upgrades in production processes to reduce carbon emissions, which involves significant capital investment. Many SMEs may lack the financial resources or technical expertise to implement these changes effectively.

- Market access: The stricter environmental regulations could impact market access, especially for companies unable to meet the new standards. This could lead to a decline in export volumes to the EU, affecting overall industry revenues.

Opportunities:

- Incentive for innovation: CBAM serves as a catalyst for the industry to adopt more sustainable practices and invest in cleaner technologies. This transition, although challenging, could improve the industry's long-term sustainability and competitiveness.

- Market positioning: By aligning with global sustainability standards, Vietnam's wood products could enhance their appeal in environmentally conscious markets. This could potentially open up new market opportunities beyond the EU.

To address the challenges posed by CBAM, the industry must prioritise the adoption of advanced technologies and sustainable practices:

Technological innovations:

- Heat pump kilns: Implementing heat pump kilns can significantly reduce carbon emissions during the kiln drying process. These kilns are more energy-efficient, reducing emissions by up to 45% compared to traditional methods. This technology not only lowers the carbon footprint but also enhances energy efficiency, resulting in cost savings.

- Blockchain-based supply chain traceability: Developing blockchain-based systems for supply chain traceability can improve transparency and ensure compliance with environmental standards. These systems enable accurate tracking of carbon emissions throughout the supply chain, facilitating better reporting and verification processes.

Sustainability practices:

- FSC and PEFC Certifications: Achieving certifications like FSC and PEFC can enhance the credibility of Vietnamese wood products in international markets. These certifications assure buyers of the sustainable and legal origins of the wood, boosting marketability.

- Renewable energy adoption: Investing in renewable energy sources, such as solar and biomass, can reduce reliance on fossil fuels and lower overall emissions. This transition not only aligns with global sustainability goals but also reduces operational costs in the long run.

- Water-based finishing systems: Adopting water-based finishing systems can significantly reduce volatile organic compound (VOC) emissions, improving air quality and worker safety. These systems are increasingly preferred in environmentally conscious markets.

6. Conclusions and policy implications

6.1. Conclusions

Recap of key challenges: Vietnam's wood export industry, a cornerstone of the nation's economy, faces a complex array of challenges that threaten its continued growth and global competitiveness. The implementation of the European Union's CBAM looms as a significant hurdle, potentially eroding the competitive advantage Vietnamese wood products have long enjoyed in the European market [5]. This challenge is compounded by the industry's current carbon-intensive practices, with total life-cycle emissions ranging from 220-280 kg CO_2e per cubic meter of finished wood products [15]. The industry's heavy reliance on energy-intensive processes, particularly in kiln drying operations which consume between 600-800 kWh of electricity per cubic meter of wood, underscores the urgent need for technological upgrades and process improvements [19, 26].

Moreover, the industry's structure, dominated by small and medium-sized enterprises (SMEs) which comprise about 90% of the total businesses, presents unique challenges in implementing large-scale environmental upgrades [1]. These smaller operations often lack the capital and technical expertise necessary for significant technological investments, making industry-wide adaptation to stricter environmental standards a formidable task. The recent decline in export revenues, from a peak of $14.8 billion in 2021 to $13.4 billion in 2023, further highlights the industry's vulnerability to global economic fluctuations and changing regulatory landscapes [1].

The industry also grapples with raw material sourcing challenges, with 30% of materials still being imported [1]. This reliance on imports not only impacts the carbon footprint through transportation emissions but also exposes the industry to supply chain disruptions and price volatilities in the global timber market. Furthermore, the varying adoption rates of sustainable practices across the industry, such as the limited implementation of reduced impact logging techniques in only 35% of logging operations, indicate a pressing need for standardisation and widespread adoption of best practices [25].

Potential adaptation strategies: In response to these challenges, several potential adaptation strategies emerge as critical pathways for the industry's sustainable growth and competitiveness. Foremost among these is the urgent need for technological innovation and modernisation across all stages of the wood production process [8]. The adoption of advanced kiln drying technologies, such as heat pump kilns which have shown potential for emission reductions of up to 45%, represents a significant opportunity for energy efficiency improvements [26]. Similarly, the expansion of biomass energy systems, currently utilised by about 60% of large-scale facilities, offers a dual benefit of waste management and carbon footprint reduction [8].

Enhancing supply chain sustainability through increased adoption of Forest Stewardship Council (FSC) certification and improved traceability systems presents another crucial strategy [19]. The implementation of blockchain-based traceability systems, as piloted by the Vietnam Forest Certification Office, has demonstrated promising results in improving traceability accuracy and reducing verification time [21]. These improvements not only address regulatory compliance concerns but also position Vietnamese wood products more favourably in environmentally conscious markets [27].

Market diversification emerges as a key strategy to mitigate risks associated with regulatory changes in specific markets [1]. While the United States remains the dominant market, accounting for 59.3% of wood exports in 2021, expanding presence in markets such as Japan, China, and other emerging economies can provide a buffer against potential market share losses in the EU due to CBAM implementation [1].

Investment in research and development, particularly in areas such as low-emission adhesives for engineered wood products and water-based finishing systems, offers pathways for significant emission reductions in manufacturing processes [11]. Collaborative efforts between industry, academia, and government research institutions will be crucial in driving these innovations forward.

Long-term outlook for Vietnam's wood export industry: The long-term outlook for Vietnam's wood export industry is cautiously optimistic, contingent upon the successful implementation of adaptation strategies and supportive policy frameworks [1]. The industry's demonstrated resilience, evidenced by investments of $2.8 billion in modern production facilities and environmental compliance measures between 2019 and 2023, suggests a strong foundation for future growth [1]. The ambitious target set by the industry to decrease emissions by 45% by 2030 compared to 2020 levels aligns with global sustainability trends and positions Vietnamese products favourably in an increasingly environmentally conscious market [26].

The continued implementation of the EU-Vietnam Free Trade Agreement presents significant opportunities for market expansion and product diversification, provided the industry can meet the stringent environmental and sustainability requirements [18, 7]. The growing global demand for sustainably sourced wood products, coupled with Vietnam's established reputation for quality and craftsmanship, creates potential for the industry to transition into higher-value, eco-friendly product segments [27].

However, the realisation of this positive outlook hinges on the industry's ability to navigate the complex interplay of technological adaptation, regulatory compliance, and market dynamics [12]. The success of large-scale manufacturers

in modernisation efforts, with average investments of $15-20 million per facility in technology and automation, sets a benchmark for the industry [11]. The challenge lies in extending these advancements across the entire sector, particularly to the numerous SMEs that form the backbone of the industry [8].

6.2. Recommendations

For Vietnamese wood export businesses: Vietnamese wood export businesses must prioritise investments in energy-efficient technologies and cleaner production processes [8]. This includes upgrading to modern kiln drying technologies, implementing biomass energy systems, and adopting water-based finishing solutions [26]. Companies should also focus on achieving international certifications, such as FSC, to enhance their products' marketability in environmentally conscious markets [18, 20].

Smaller enterprises should explore collaborative models, such as forming cooperatives or industry clusters, to pool resources for technology investments and shared facilities [11]. This approach can help overcome the financial barriers to adopting advanced, low-emission technologies.

Businesses should also invest in workforce training and development, focusing on skills related to sustainable production practices, carbon accounting, and international environmental standards compliance [27]. Engaging with international partners for knowledge transfer and capacity building can accelerate this process.

For the Vietnamese government: The Vietnamese government plays a crucial role in facilitating the industry's transition [27]. Policymakers should consider expanding and simplifying access to financial incentives for green technology investments, particularly for SMEs [23]. This could include low-interest loans, tax breaks for investments in emission-reduction technologies, and grants for research and development in sustainable wood processing techniques.

Developing a comprehensive roadmap for the industry's green transition, aligned with national environmental goals and international commitments, is essential [28]. This should include clear milestones, support mechanisms, and regulatory frameworks to guide the industry's evolution.

The government should also prioritize international negotiations, particularly with the EU, to secure favourable terms under CBAM and explore possibilities for mutual recognition of environmental standards and certifications [6, 8]. Strengthening domestic forestry management to increase the supply of sustainably sourced timber can reduce reliance on imports and improve the industry's overall sustainability profile [1].

For international cooperation and support: International cooperation will be crucial in facilitating Vietnam's wood industry transition [26]. Bilateral and multilateral agreements should focus on technology transfer, capacity building, and financial support for emission reduction initiatives. International organisations and development agencies can play a key role in providing technical assistance and funding for pilot projects in sustainable wood processing and forest management [20].

Collaborative research initiatives between Vietnamese institutions and international partners should be encouraged to develop innovative, low-emission technologies tailored to the specific needs of Vietnam's wood industry [11]. This could include joint research programs, exchange of experts, and shared laboratories for testing and developing new materials and processes.

6.3. Future research directions

The dynamic nature of global climate regulations and their impact on international trade necessitates ongoing research to inform industry strategies and policy decisions [4]. A priority area for future research is a comprehensive quantitative assessment of CBAM's impact on Vietnam's wood industry [18]. This should include detailed economic modelling of various CBAM implementation scenarios, considering factors such as different carbon price levels, potential exemptions, and the industry's adaptation pace. Such research would provide valuable insights for both policymakers and industry stakeholders in developing targeted mitigation strategies.

Comparative studies with other affected sectors or countries could offer valuable lessons and best practices for Vietnam's wood industry [17]. Research comparing the adaptation strategies and outcomes in sectors such as steel, cement, or aluminium, which are directly targeted by CBAM, could provide insights into effective policy measures and technological solutions [16]. Similarly, studying the responses of other wood-exporting countries, particularly those with similar economic structures to Vietnam, could inform more effective national strategies.

Lastly, research into the long-term sustainability of the global wood trade under evolving climate regulations is crucial [12]. This should encompass analysis of shifting consumer preferences towards sustainable products [27], the potential emergence of new wood-based materials with lower carbon footprints [11], and the impact of reforestation and afforestation efforts on global wood supply chains [15, 16]. Additionally, exploring the potential for circular economy principles in the wood industry, such as advanced recycling technologies and waste-to-energy solutions, could uncover new avenues for sustainability and competitiveness [11, 23].

COMPETING INTERESTS

The author declares that there is no conflict of interest regarding the publication of this article.

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