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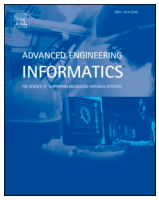

Investigating the carbon border adjustment mechanism transition process with linguistic summarization method: A situational analysis of exporting countries

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ABSTRACT

The Paris Agreement holds significant importance since it establishes a global framework for addressing the issue of climate change and endeavors to mitigate the release of greenhouse gases. The Carbon Border Adjustment Mechanism was introduced as an integral component of this agreement, aiming to oversee the carbon emissions associated with imported items within the European Union and provide compensation for the emissions from the nations engaged in importation. It is essential to analyze the countries involved in exporting to the European Union within the Carbon Border Adjustment Mechanism context to mitigate carbon leakage and effectively support the objectives outlined in the Paris Agreement. This research investigated 104 nations engaged in exporting activities to 27 European Union member countries. The linguistic summarization method, a descriptive data analytics tool, was employed for the analysis. A total of 42 Combined Nomenclature codes were encompassed within the scope of evaluation throughout the transition phase of the Carbon Border Adjustment Mechanism. This study examines the characteristics of exporting nations based on three variables: The Environmental Performance Index, a sustainability indicator; the Region in which the countries are located as classified by the World Bank; and the quantity of Renewable Energy Consumption. Additionally, the study explores the characteristics of EU countries, focusing on their Environmental Performance Index score and geography. The study employed fuzzy sets and the fuzzy c-means algorithm as parts of the linguistic summarization technique. Polyadic quantifiers were used to extract linguistic summaries, resulting in the acquisition of 124,227 summaries. A total of 1594 summaries have a truth degree exceeding 0.9. The findings were effectively utilized to assess the influence of the linguistic summarization approach and offered a valuable viewpoint for decision-makers needing more expertise in this domain.

1. Introduction

The Paris Agreement, approved in 2015 under the auspices of the United Nations Framework Convention on Climate Change, entails substantial responsibilities in addressing the adverse effects of climate change. The 196 nations that ratified the agreement have established a shared objective of restricting the rise in worldwide temperatures to a maximum of two degrees Celsius over levels observed during the pre-industrial era, with an aspirational target of 1.5 degrees Celsius if feasible. The Green Deal initiative, which supplements the objectives outlined in the Paris Agreement, endeavors to achieve carbon neutrality in Europe by the year 2050. Furthermore, it seeks to reduce net greenhouse gas emissions by 55 % compared to the levels recorded in 1990 by 2030.

Abbreviations: AGE, Applied General Equilibrium; CBAM, Carbon Border Adjustment Mechanism; CGE, Computable General Equilibrium; CN, Combined Nomenclature; COMTRADE, Commodity Trade Statistics Data Base; EC, Exporter Country; EFTA, European Free Trade Association; EPI, Environmental Performance Index; ETS, Emissions Trading Scheme; EU, European Union; LS, Linguistic Summarization/Summary; IO, Input-Output; QFM, Quantifier Fuzzification Mechanism; REC, Renewable Energy Consumption; US, United States; TD, Truth Degree.

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Implementing these restrictions has prompted European Union (EU) countries to adopt more sophisticated emission reduction techniques, resulting in the relocation of production in emission-intensive industries to countries beyond the EU. The phenomenon known as carbon leakage has prompted the development of the Carbon Border Adjustment Mechanism (CBAM) to safeguard EU commerce. According to the framework of the CBAM, EU regions will implement a carbon tax on imports from non-EU regions. Alternatively, these imports may be incorporated into the EU Emission Trading System. The primary objective of the CBAM is to address the issue of carbon leakage by ensuring parity in carbon pricing between domestically produced and imported goods [30]. CBAM will commence its transition phase on October 1, 2023. This agreement is relevant to nations that export goods to EU member states.

Literature research on the subject is first provided to highlight the current situation. Chen and Guo [7] used the Computable General Equilibrium (CGE) model to assess the impact of carbon tariffs on China's trade in industrial goods for scenarios in which the US, EU, and Japan imposed carbon tariffs concurrently or separately, and Bao et al. [4] evaluated the effects of a carbon-based border tax to be implemented by the US and EU using CGE. Fouré et al. [13] used the general equilibrium model − MIRAGE to assess the potential effects of implementing a carbon pricing mechanism on imports of energy-intensive goods in the EU and the European Free Trade Association (EFTA) countries.

The immediate effects of CBAM using a multi-regional input–output (IO) analysis on inequality in plastics trade were analyzed by Ren et al. [28], and its impact on the value of exports to the EU market was studied by Zhong and Pei [41]. The results revealed that introducing CBAM would result in a reallocation of competitiveness among various countries and regions.

Kuo and Chou [21] used a regression model to examine the relationship between international trade, various economic factors, and the carbon emissions of multinational companies in Taiwan. The study revealed strong positive correlations between variables, including profitability and the annual growth rate of export trade. Acar et al. [1] applied a dynamic and multi-sectoral Applied General Equilibrium (AGE) model to investigate the comprehensive macroeconomic impacts of the Green Deal on the Turkish economy.

In the literature, there are studies on the impact of CBAM on countries' trade and economic situation. Kuusi et al. [22] studied CBAM for Finland and the EU, Kuehner et al. [20] for German stakeholders, and Lestan et al. (2022) for Russia [23].

It is vital to elucidate the significant alterations that will transpire in CBAM. A limited number of research assess some countries [26,28,41]. Further investigation is warranted in this particular domain. Nevertheless, it is worth noting that most of the research examined in this analysis uses CGE models. On the other hand, utilizing IO models is the second most commonly employed approach [41]. Hence, utilizing and assessing novel methodologies and frameworks in implementing and evaluating CBAM are essential and required.

The evaluation and interpretation of massive data about countries, encompassing their properties and interrelationships, necessitates using data mining techniques. Data mining techniques, particularly descriptive data mining methods, derive statistical summaries from datasets, such as the mean and standard deviation. Additionally, they can generate descriptive-based Linguistic Summaries (LSs) that are more easily retained and recalled [15,35]. Acknowledging, conveying, and including descriptive-based summaries, such as "most EU countries have high Renewable Energy Consumption (REC)," is crucial in decision-making procedures.

Linguistic Summarization (LS) is a method proposed by Yager [38] and has been effectively implemented across various domains. One of the proposed methodologies for quantifying language terms such as "most" and "low" in the context of LS is the employment of fuzzy sets, as introduced by Zadeh [40]. Using fuzzy sets enables the representation of database features in language expressions. LSs have been successfully applied in various domains of research, including sales data [19], investment funds [18], Kansei engineering [2], human behavior modeling [3], time series [17], sensor data for elderly care [36], and international trade network analysis [14]. Please refer to Delgado et al. [9] and Boran et al. [6] for more information. Although this approach has yielded positive outcomes, its application in analyzing data-intensive processes such as sustainable development and CBAM is still limited.

Given the existing body of literature, the objective of this study is to employ the LS approach to investigate the exports and various attributes of countries that export to the EU. This analysis will encompass all product groups within the six sectors subject to the CBAM during the transition period. This study expands the methodologies applicable to ongoing discussions utilizing the LS approach. It presents a more comprehensive analysis based on the CBAM framework, which has been underrepresented in the prior literature primarily focused on CGE-based investigations. Our methodology facilitates the creation of the application framework within the expanding body of literature on CBAM. Nevertheless, the offered application comprehensively analyses the countries' conditions by collectively assessing many countries. This topic regarding the CBAM has yet to receive much attention in the literature. The subsequent sections of the study are organized as follows. The second section introduces fuzzy sets and LS, while the third section outlines the technique and application steps. The fourth chapter presents the results and discussions, while Chapter 5 concludes the study.

2. Preliminaries

Within this section, the fundamental concepts of fuzzy sets, basic LS, and linguistic network summarization procedures are dissected into successive subsections to provide a more comprehensive elucidation.

2.1. Fuzzy sets

Zadeh [40] introduced fuzzy sets as a solution for overcoming the limitations of standard binary set theory. Unlike classical sets, which categorize components as either belonging to or not belonging to a set, fuzzy sets allow for a more sophisticated approach to modeling uncertainty and vagueness. Fuzzy sets assign degrees of membership to elements, representing the extent to which an element belongs to a set on a scale from 0 to 1. On universe X, a fuzzy set A is defined as $A = \{\langle x, \mu_A(x)\rangle | x \in X\}$. Here, the membership degree of x is presented with a mapping function from the universe to the unit interval as $\mu_A(x) : X \rightarrow [0,1]$. An alpha-cut enables you to extract a crisp subset of elements from a fuzzy set with membership degrees greater than or equal to a given threshold number (often abbreviated with α). The $\alpha-$cut of a fuzzy set A, is defined as $A_\alpha = \{x \in X | \mu_A(x) \geq \alpha\}$.

2.2. Basic linguistic summarization

As proposed by Yager [38], LS is a technique that condenses enormous amounts of data into short and human-readable natural language forms. Unlike traditional data summary approaches, which focus on extracting mean, median, and standard deviation, LS uses natural language processing and generation to provide summaries that look like human-written material. The human-written material follows a sentence structure. Zadeh [39] proposed two summary structures: type-I and type-II quantified sentences.

Type-I quantified sentence is "Q Ys are/have A. [TD]." Here, Q is a linguistic quantifier labeled with a fuzzy set, Y is the set of objects, $Y = \{y_1, y_2, \cdots, y_M\}$, A is a summarizer about the set of attributes $S = \{s_1, s_2, \cdots, s_K\}$, TD is the truth degree of the sentence and calculated using Eq. (1).

$$TD = Q\left(\frac{\sum_{m=1}^{M} \mu_A(y_m)}{r}\right) \quad (1)$$

where r is equal to 1 for absolute quantifiers and M for relative quantifiers. As examples, absolute and relative fuzzy quantifiers are presented in Fig. 1a and Fig. 1b, respectively.

Type-II quantified sentence is "Q B Ys are/have A. [TD]." Here, Q is a linguistic quantifier labeled with a fuzzy set, Y is the set of objects, $Y = \{y_1, y_2, \cdots, y_M\}$, A and B are summarizers and pre-summarizer about the set of attributes $S = \{s_1, s_2, \cdots, s_K\}$, TD is the truth degree of the sentence and calculated using Eq. (2).

$$TD = Q\left(\frac{\sum_{m=1}^{M}(\mu_A(y_i) \wedge \mu_B(y_i))}{\sum_{m=1}^{M}\mu_B(y_i)}\right) \tag{2}$$

where $\wedge$ intersects two fuzzy sets $\mu_A(y_i)$ and $\mu_B(y_i)$.

2.3. Linguistic network summarization

The interactions between the various interrelated elements that make up networks are frequently complex and multidimensional. In LS, polyadic quantifiers can be used to encode intricate relationships in such statements, including those with multiple quantifiers and relations between objects [27,31]. It is important to explain polyadic quantification in monadic quantifiers, which employ Boolean combinations and iterative operators, to work with it in natural language. The iteration operator is defined formally as $It(Q, Q^{'})[A, B, R] \Leftrightarrow Q[A, \{a|Q^{'}[B, R_{(a)}]\}]$. Here Q and $Q^{'}$ are generalized quantifiers, A and B are subsets of the universe, R is a binary relation over the universe, and $R_{(a)} = \{b|R(a,b)\}$. For instance, "Most of the EC countries exports to most EU countries with high EPI." represents a polyadic quantification, and iteration can be employed to convey its underlying meaning. The "export" relation connects the EC countries and EU countries. This sentence holds under one interpretation if and only if there exists a set that contains the majority of EC countries, and within this set, each EC country exports any amount of products to the majority of EU countries.

To summarize network data, Genç et al. (2020) proposed a novel methodology that employs semi-fuzzy quantifiers to assess summaries formulated as polyadic quantifications. The summary forms were evaluated using a unique assessment technique called the semi-fuzzy quantifiers-based evaluation approach [10]. The semi-fuzzy iteration operator in the summary form "Q A Y s are in R with $Q^{'}B$ Y s" is defined as $It(Q, Q^{'})[A, B, R] \Leftrightarrow Q[A, \{a|Q^{'}[B, R_{(a)}]\}]$, where Q and $Q^{'}$ are semi-fuzzy quantifiers, A and B are the fuzzy subsets of the universe X for the attributes v_1 and v_2, R is a fuzzy relation, $R_{(x_i)} = \{x_j|R(x_i, x_j)\}$, and F is a Quantifier Fuzzification Mechanism (QFM).

A probabilistic QFM, F^I, is defined as in Eq. (3) for finite cases, where $X_S(s = 1, 2, \cdots, S)$ is a fuzzy property, $(X_S)_{\alpha_s}$ is an α cut of X_S, $0 = \alpha_{s,m_s+1} < \alpha_{s,m_s} < \cdots < \alpha_{s,1} < \alpha_{s,0} = 1$ and the mass assignment corresponding to $\alpha_{s,j}$ is defined as $m(\alpha_{s,j}) = \alpha_{s,j} - \alpha_{s,j+1} (j = 0, 1, 2, \cdots, m_s)$. Mass assignments might be interpreted as a probability distribution. Initially, it was defined as a confidence measure by Martin and Yun (2009) [24]; however, it could be used to evaluate LSs later. Eq. (4) provides the fuzzy value for TD. For more information, refer to Genc et al. [14].

$$F^I(Q)(X_1, \cdots, X_S) = \sum_{i_1=0}^{m_1} \cdots \sum_{i_S=0}^{m_s} Q\Big((X_1)_{\alpha_{1,i_1}}, \cdots, (X_S)_{\alpha_{s,i_s}}\Big) m(\alpha_{1,i_1}) \cdots m(\alpha_{s,i_s}) \tag{3}$$

$$It(Q, Q^{'})[A, B, R] \Leftrightarrow \sum_{i_3=0}^{m_3} \sum_{i_4=0}^{m_4} Q(A_{\alpha_3, i_3}$$

$$\sum_{i_1=0}^{m_1} \sum_{i_2=0}^{m_2} Q^{'}\Big(B_{\alpha_{1,i_1}}, R_{(x_i)\alpha_{2,i_2}}\Big) m(\alpha_{1,i_1}) m(\alpha_{2,i_2})_{\alpha_{4,i_4}}) m(\alpha_{3,i_3}) m(\alpha_{4,i_4}) \tag{4}$$

The fundamental principle within this paradigm revolves around the semi-fuzzy iteration operator, which articulates the significance of a polyadic quantification by considering its constituent elements individually. For instance, "Most EU member states import low quantities of products from countries that serve as exporters." In this statement, the term "import" denotes a connection between two sets, namely "ECs and EUs" (referring to countries) and "products." To ascertain the legality of a sentence under a specific interpretation, it is necessary for a set to encompass the majority of ECs, each of which engages in the exportation of multiple products.

3. Materials and methods

3.1. Methodology overview

The approach employed in this study was executed through a series of five sequential steps. The initial stage involves identifying the nations to be considered in the analysis and the nodes and connections that will define the attributes of these countries in the CBAM framework. Once the data has been gathered, the subsequent stage involves the identification of fuzzy quantifiers and linguistic phrases to introduce a degree of ambiguity to the data. The third phase involved analyzing massive data through the LS and acquiring complementing summaries. During the fourth stage, the obtained summaries underwent a filtration process based on their level of truth. Subsequently, LSs that demonstrated high accuracy were chosen for further interpretation. The final stage of the process was the presentation and interpretation of the acquired summaries. The study's summary is presented in Fig. 2.

3.2. Implementation

The implementation steps, according to the flow chart, are outlined below.

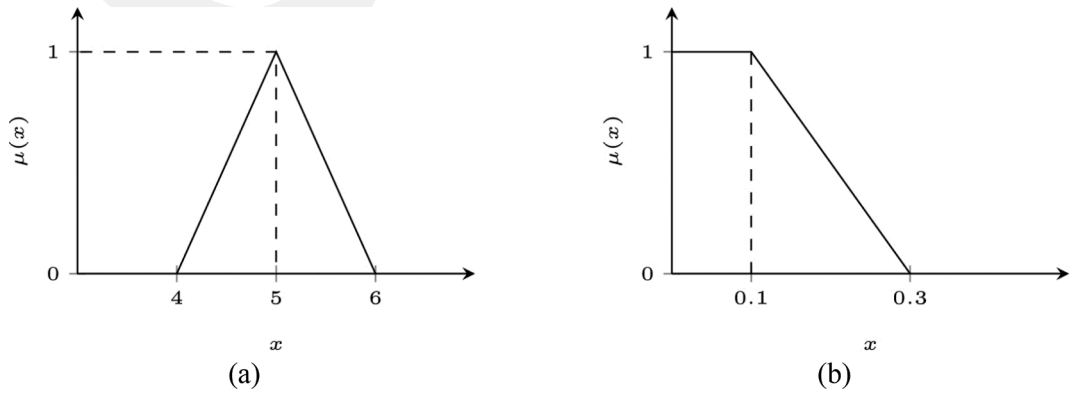

Fig. 1. (a) Absolute quantifier "about 5", (b) relative quantifier "few".

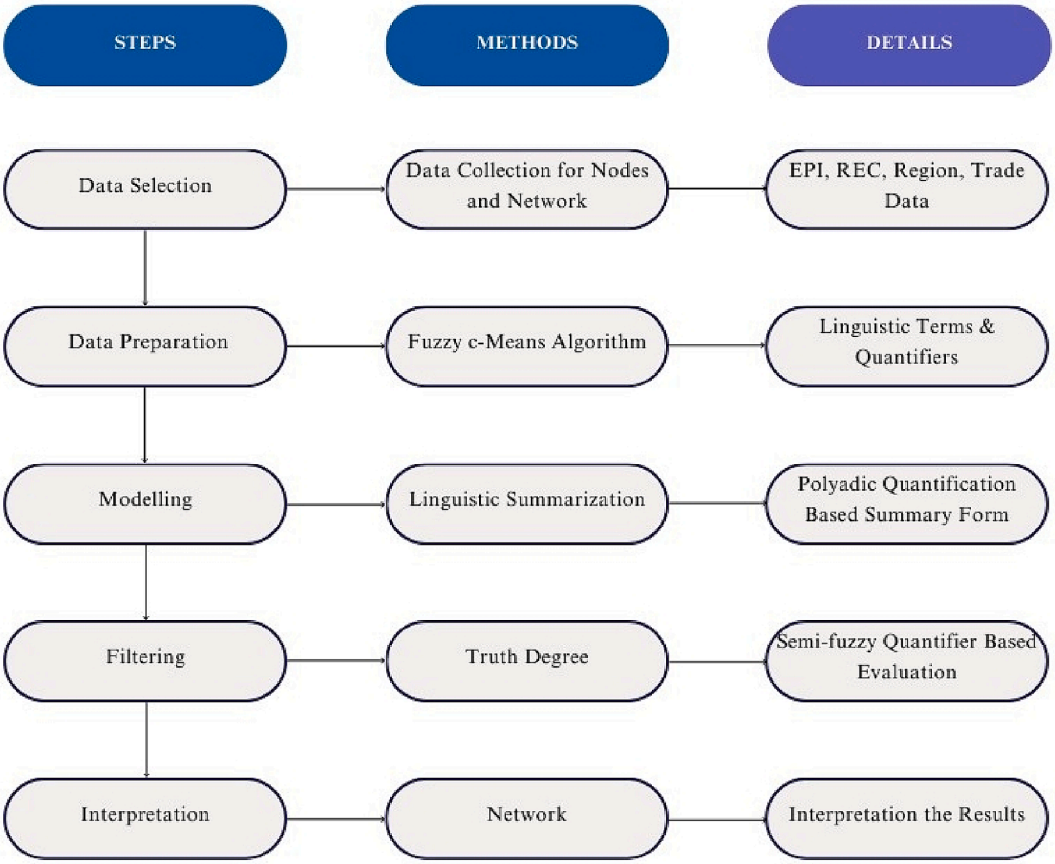

Fig. 2. The steps, methods, and details followed in the study.

3.2.1. Data selection

In this phase, the countries that will partake in the examination and then determining the criteria possessed by these countries were identified. The selection of countries was based on their EU Exports by Country in US Dollars exceeding $1 billion, as reported in the United Nations COMTRADE international trade database (Trading [33]. The dataset pertains to 2021 (Table S.1 List of Country in Supplementary Document). Based on the information provided by this database, it was found that 177 countries export goods to countries within the EU. Out of the total number of nations under consideration, a subset of 88 countries exporting goods worth more than 1 billion dollars was initially intended to be included in the study. However, due to insufficient data availability, 11 countries were subsequently eliminated from the research, resulting in a final sample size of 77 countries. EU and exporter countries (ECs) are given in Table 1.

The networks and nodes of these countries were determined to analyze the correlation among the chosen nations concerning CBAM. The selection of network data for the study was based on import value (measured in thousands of USD), as this variable is directly correlated with the concept of CBAM. CBAM, in essence, is a system predicated upon the foundation of international trade. Hence, CBAM is affected by a significant correlation between the attributes of countries and their trade connections. To consider this correlation, countries that had exported to the EU exceeding 1 billion dollars were chosen with a specific focus on six sectors within the scope of CBAM. The variables utilized in this study include the Environmental Performance Index (EPI), regional categorization, and the REC to examine their impact on CBAM.

The EPI is a collaborative ranking system developed through a partnership between Yale University, Columbia University, the World Economic Forum, and the European Commission Joint Research Center. Its primary objective is to assess and evaluate different countries' environmental performance. The EPI is a tool that assesses countries' environmental performance in terms of their efforts to safeguard human health and maintain the vitality of ecosystems [12]. Within the framework of CBAM, incorporating EPI is crucial for evaluating a nation's ecological consciousness and endeavors towards sustainability, where a greater EPI score signifies a more favorable stance in CBAM implementations.

Table 1
EU countries and ECs.

EU Country	EC
Austria, Belgium, Bulgaria, Croatia, Cyprus, Czech, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden.	Albania, Algeria, Angola, Argentina, Australia, Azerbaijan, Bahrain, Bangladesh, Belarus, Bosnia And Herzegovina, Brazil, Burkina Faso, Cambodia, Cameroon, Canada, Chile, China, Colombia, Congo, Costa Rica, Cuba, Dominican Republic, Ecuador, Egypt, Ethiopia, Georgia, Ghana, Guatemala, Iceland, India, Indonesia, Iran, Iraq, Israel, Japan, Jordan, Kazakhstan, Kenya, Korea, Republic of, Kuwait, Lebanon, Liberia, Macedonia, North, Malaysia, Mali, Mexico, Moldova, Montenegro, Morocco, New Zealand, Nigeria, Norway, Oman, Pakistan, Panama, Peru, Philippines, Qatar, Russian Federation, Saudi Arabia, Senegal, Serbia, Singapore, South Africa, Sri Lanka, Switzerland, Thailand, Togo, Tunisia, Türkiye, Ukraine, United Arab Emirates, United Kingdom, United States of America, Uruguay, Uzbekistan, Viet Nam.

REC refers to the proportion of renewable energy sources in a nation's final energy consumption. The data utilized in this study is sourced from Word Bank, with the most recent data accessible being 2022 [16]. Utilizing a high amount of REC is a significant factor that benefits the execution of CBAM, as it indicates that a nation's manufacturing methods are ecologically sustainable and diminish its carbon emissions.

The region attribute considered the region classification provided by the World Bank [37]. The World Development Indicators categorize all 189 member countries of the World Bank and an additional 28 countries with populations exceeding 30,000 based on their income level and geographic location. This classification facilitates the presentation of fundamental statistical information, enabling users to gather, categorize, and compare data as required. Interregional disparities play a crucial role in comprehending the impacts of environmental regulations and ensuring equilibrium in international trade among countries in different geographical areas. Hence, regional classification plays a crucial role in implementing CBAM by harmonizing environmental consequences and fostering equitable trade. The study incorporates the geographical regions of The World Bank, namely Europe & Central Asia, Middle East & North Africa, Sub-Saharan Africa, Latin America & Caribbean, East Asia & Pacific, South Asia, and North America. Table S.2 Nodes Data in the Supplementary Document gives all nodes' data [16].

The determination of the goods included in the study was based on the consideration of Regulation (EU) 2023/956 of the European Parliament and Council, which pertained to establishing a carbon border adjustment system and was issued on May 10, 2023. The goods for identification purposes are listed in Annex I of this rule, including the Combined Nomenclature (CN) codes. The CN codes refer to Regulation (EEC) No 2658/87 and serve as a categorization system that caters to the requirements of the Common Customs Tariff and the external trade statistics of the EU. The CN codes and description of CBAM regulation are given in Table S.3 CN Codes in supplementary document [8].

The nations' exports of the specified CN codes were sourced from the UN Comtrade Database [34]. The EU's CBAM law incorporates specific exemptions for certain sub-CN codes inside the broader CN code framework. In this scenario, the import quantities of the eliminated CN codes are deducted from the overall import sum of the primary category. The import values are denominated in USD Thousands and pertain to 2022. The data about CN number 2507.00.80 was collected under the classification code 250,700 due to database limitations preventing more detailed categorization. A comprehensive collection of imports was gathered from 27 EU member countries, in addition to 77 countries engaged in exporting activities. These imports encompassed 42 distinct CN codes.

3.2.2. Data preparation

Import numbers consist of numerical quantities accompanied by the country's corresponding characteristics. fuzzy sets have been employed to include the inherent uncertainty present in data and convert it into linguistic representations. the fuzzy c-means technique acquired fuzzy sets [5]. It autonomously ascertains fuzzy sets and their accompanying membership functions after assigning linguistic terms (low, medium, and high) to each fuzzy set. In a similar vein, the aggregate import quantities of nations are linguistically represented through the partitioning of these quantities into fuzzy sets denoted as "few", "half", and "most." Fig. 3 explains nodes and node properties.

The quantifiers "most", "half", and "few" have been seen as significant in academic discourse. These quantifiers are typically represented and analyzed in Eq. (5), Eq. (6), and Eq. (7), respectively.

$$Q_{most}(x) = \begin{cases} 0 & x \le 0.5 \\ \dfrac{x-0.5}{0.25} & 0.5 < x \le 0.75 \\ 1 & x > 0.75 \end{cases} \tag{5}$$

$$Q_{half}(x) = \begin{cases} 0 & x \le 0.25 \\ \dfrac{x-0.25}{0.25} & 0.25 < x \le 0.5 \\ \dfrac{0.75-x}{0.25} & 0.5 < x \le 0.75 \\ 0 & x > 0.75 \end{cases} \tag{6}$$

$$Q_{few}(x) = \begin{cases} 1 & x \le 0.25 \\ \dfrac{0.5-x}{0.25} & 0.25 < x \le 0.5 \\ 0 & x > 0.5 \end{cases} \tag{7}$$

Employing the fuzzy c-means algorithm, linguistic labels of the variables are obtained through MATLAB [25]. The membership functions representing the related fuzzy sets of each attribute are given in Fig. 4.

3.2.3. Modelling

The research used the polyadic quantification-based LS method to

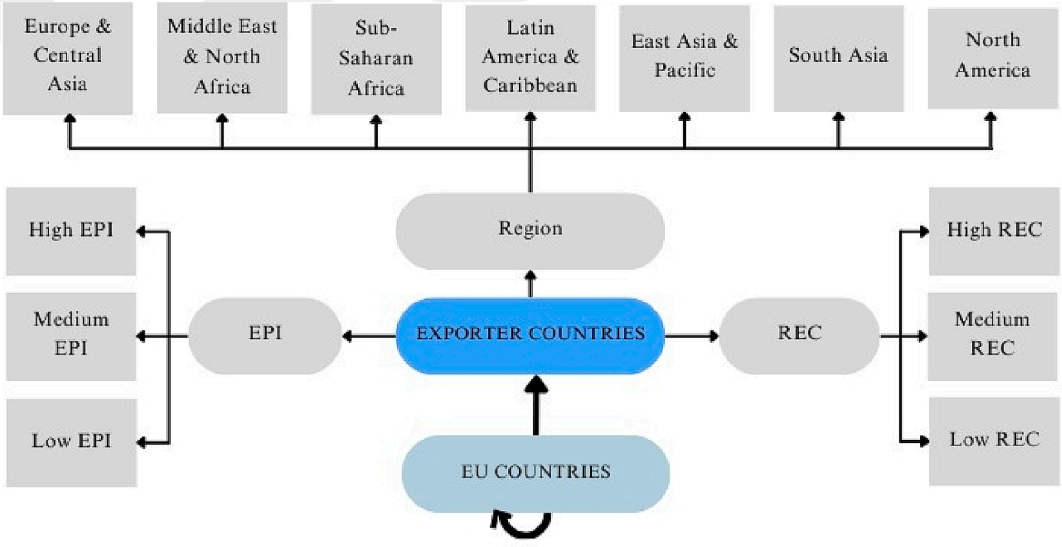

Fig. 3. The nodes and node properties in the network representation.

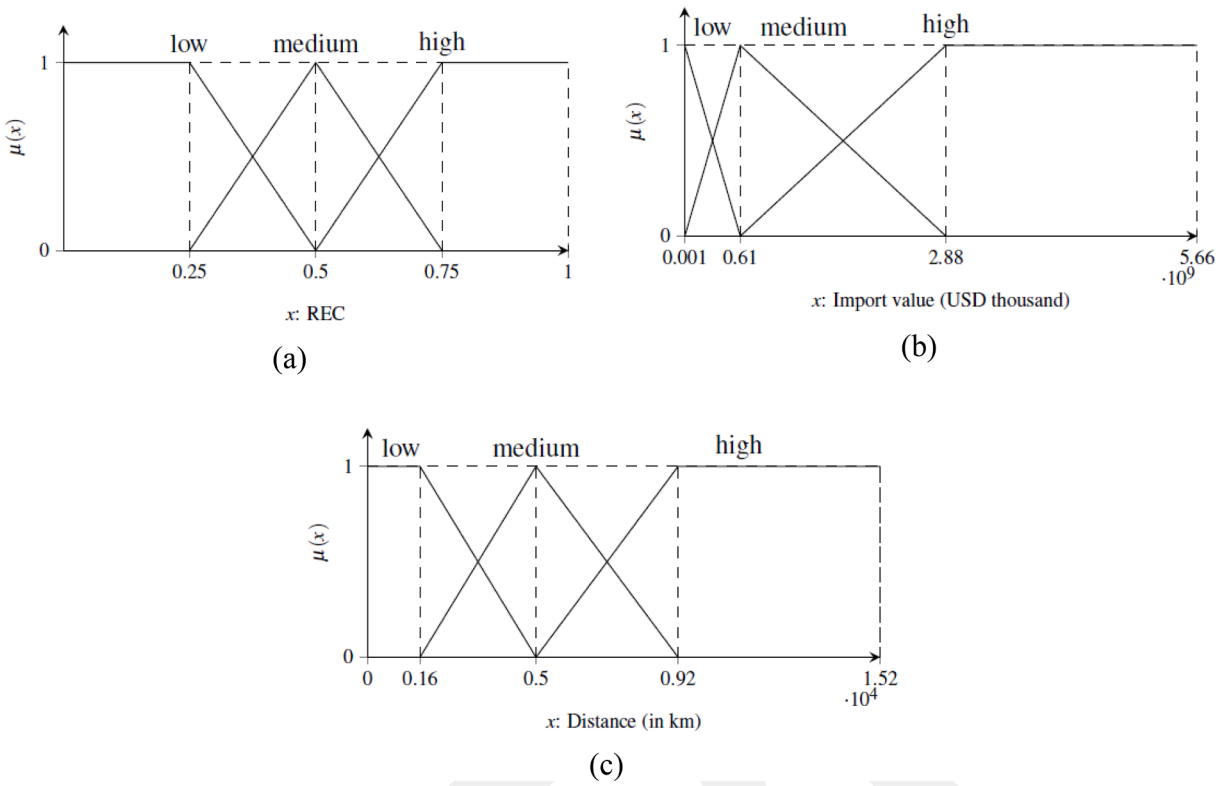

Fig. 4. The fuzzy membership functions of the variables: (a) REC, (b) import value, (c) EPI.

represent and analyze exporting data connected from EC countries to EU countries throughout the modeling phase of the methodology. Extracting significant patterns and structures from the data entails applying Eq. (4).

3.2.4. Filtering

During the fourth step of the application, the TD was employed as a criterion to selectively refine the summaries acquired during the modeling phase. The examination of summaries is the most crucial phase in LS [6]. In most approaches, the evaluation of summaries is conducted based on their level of correctness. This research used a TD of 0.9 as the threshold for evaluating summaries. Only summaries with a TD equal to or more than this number were evaluated.

3.2.5. Interpretation

The LSs acquired during the final phase are analyzed and elaborated upon in the subsequent section.

4. Results and discussion

The LSs for all potential combinations of quantifiers and summarizers were generated using MATLAB[25]. In the modeling phase, algorithmic codes were developed to generate all possible combinations of quantifiers and summarizers. The algorithm was executed using the MATLAB programming environment. The following subsections present the study's results and a detailed discussion.

4.1. Results

A comprehensive dataset of 124,227 language summaries was collected, encompassing interactions between EU member states and 104 nations engaged in exporting activities. A total of 1594 summaries were acquired, each possessing a TD exceeding 0.9. The analysis incorporates one network data variable: import relation (measured in USD Thousand). All summaries are given in Table S.4 LS List in the Supplementary Document.

Table 2 illustrates the attributes that generate the 1594 summaries acquired from the import value. The summaries acquired pertain exclusively to the regions of Europe and Central Asia, the Middle East, and North Africa. This outcome is anticipated, given that the EU member states are in this geographical region. Nevertheless, due to the elevated EPI values observed in EU countries, summaries were again acquired for this cohort. The findings of this study indicate that EU member states exhibit a better EPI than countries primarily engaged in exporting activities. Consequently, a primary objective of the CBAM application is to enhance the significance that exporting nations attribute to sustainability and expedite their efforts in addressing climate change [30,32].

A binary matching procedure was employed to align the features of ECs with those of EU countries. Subsequently, a combining process was conducted to understand the LSs derived from this matching. Given that the TD was assigned as 0.9, it was determined that if the value of the combined summaries was within the range of 0.9–0.99, the least number considered would be 0.9. Table 3 shows generated LSs for REC and EPI. The number denotes the quantity of LSs that were generated.

According to ECs' REC levels, summaries are obtained only for ECs that consume low REC. For EPI, the sustainability qualifier of importing EU countries, LSs were obtained only for high EPI countries. LSs were obtained for all CN codes (42) examined for the low amount of exports from countries with low REC to EU countries with high EPI. For the medium export rate, LSs were prepared for 15 CN codes from a few ECs with low REC to EU countries with few high EPI. Finally, the high export amount was obtained only for the pr7: Electrical energy and pr42: Iron and steel product groups among the countries with the specified qualifications.

LSs obtained for the regions of EU countries according to the REC status of ECs are given in Table 4. Since EU countries are located in Europe, Central Asia, the Middle East, and North Africa, according to the World Bank's distinction, LSs were obtained only for these regions.

Based on the data presented in Table 4, it can be observed that a total of 180 LSs were acquired for exports to EU countries in the regions of

Table 2
Summary of the generated LSs for import relation between EC and EU countries.

		EU Countries									
		Low EPI	Medium EPI	High EPI	East Asia and the Pacific	Europe and Central Asia	Latin America and the Caribbean	Middle East and North Africa	North America	South Asia	SubSaharan Africa
EC Countries	Low REC			×		×		×			
	Medium REC					×		×			
	High REC					×		×			
	Low EPI					×		×			
	Medium EPI					×		×			
	High EPI					×		×			
	East Asia and the Pacific					×		×			
	Europe and Central Asia					×		×			
	Latin America and the Caribbean					×		×			
	Middle East and North Africa					×		×			
	North America					×		×			
	South Asia					×		×			
	SubSaharan Africa					×		×			

Table 3
Generated Linguistic Summaries for REC values of EC countries and EPI of EU countries.

Summaries	TD
Exports of most ECs with low REC to most EU countries with high EPI for pr12, pr13, pr22, pr26, pr27, pr32, pr33, pr42 are low	0.9
Exports of most ECs with low REC to most EU countries with high EPI for pr1, pr2, pr3, pr4, pr5, pr6, pr7, pr8, pr9, pr10, pr11, pr14, pr15, pr16, pr17, pr18, pr19, pr20, pr21, pr23, pr24, pr25, pr28, pr29, pr30, pr31, pr34, pr35, pr36, pr37, pr38, pr39, pr40, pr41 are low	1
Exports of a few ECs with low REC to a few EU countries with high EPI for pr5, pr19, pr20, pr22, pr24, pr25, pr27, pr28, pr30, pr33, pr34, pr35, pr39, pr41 are medium	0.9
Exports of a few ECs with low REC to a few EU countries with high EPI for pr7, pr42 are high	1

pr: product group.

Europe and Central Asia. These summaries were derived from low REC ECs, medium REC ECs, and high REC ECs, yielding 59, 59, and 62 summaries, respectively. Low exports from ECs with low REC are obtained as most EC to most EU countries, which is the most inclusive language qualifier for all CN codes examined. The findings suggest that all products falling under the purview of CBAM are exported to EU nations, albeit to a limited degree.

Fifteen CN codes were identified for the medium export amounts from a few EC countries with low REC to a few EU countries. The findings of this study suggest that while the importation of goods classified under these CN codes by EU member states is substantial, the number of countries engaged in such import activities is fewer than the total number of countries investigated.

The evidence indicates that to mitigate the impact of the CBAM, EU member states characterized by low levels of REC and significant exports of such products should procure their energy from more environmentally sustainable sources.

Comparable findings were observed in nations characterized by a medium and high utilization of renewable energy sources. The obtained LSs indicate that EC countries primarily export pr12: Fertilizers; mineral or chemical and nitrogenous, associated with higher levels of REC than other products. LSs indicate that the primary goods exported by countries with medium to high levels of REC are pr7: Electrical energy and pr42: Iron and steel. Fifty-nine LSs were collected about exports to EU nations in the Middle East and North Africa region from countries with low levels of REC. Similarly, 59 LSs were obtained from countries with medium levels of REC, while 62 LSs were gathered from countries with high levels of REC. The findings derived from the EU countries within the Europe and Central Asia region were similarly observed within the EU countries situated in the Middle East and North Africa region.

Table 5 presents the findings on the EPI values of the ECs and the importing EU countries' regions. Sixty-two LSs about exports from countries with low EPI to EU countries in Europe and Central Asia were collected. Additionally, 60 LSs were obtained for exports from countries with medium EPI, while 22 were gathered for exports from countries with high EPI. Fifty-three LSs were collected on exports to EU nations in the Middle East and North Africa region from countries with low EPI. Additionally, 61 LSs were obtained from countries with medium EPI, while 51 were gathered from countries with high EPI. Exports from countries with low, medium, and high EPI to EU countries are observed across all CN codes. However, there is a negative correlation between the volume of exports and the number of ECs. LSs were obtained exclusively for "low" export quantities in "most" EC countries, ensuring the most comprehensive qualifier. Summaries possessing a TD of 1 are applicable to 42 CN codes when derived from low EPI EC. However, this number reduces to 34 and 11 when the summaries are generated from medium EPI and high EPI, respectively. The product groups that exhibited high levels of exports were found to be independent of the EPI value. Specifically, these product groups were identified as pr7: Electrical energy and pr42: Iron and steel. Based on the data in Table 5, it is

Table 4
Generated LSs for REC value of EC countries and Region of EU countries.

Summaries	T	D
Exports of **most** ECs with *low REC* to **most** EU countries in **Europe and Central Asia** for pr22, pr27, pr42 are **low**		0.9
Exports of **most** ECs with *low REC* to **most** EU countries in **Europe and Central Asia** for pr1, pr2, pr3, pr4, pr5, pr6, pr7, pr8, pr9, pr10, pr11, pr12, pr13, pr14, pr15, pr16, pr17, pr18, pr19, pr20, pr21, pr23, pr24, pr25, pr26, pr28, pr29, pr30, pr31, pr32, pr33, pr34, pr35, pr36, pr37, pr38, pr39, pr40, pr41 are **low**		1
Exports of a **few** ECs with *low REC* to a **few** EU countries in **Europe and Central Asia** for pr5, pr7, pr19, pr20, pr22, pr24, pr25, pr27, pr28, pr30, pr33, pr34, pr35, pr39, pr41 are **medium**		0.9
Exports of a **few** ECs with *low REC* to a **few** EU countries in **Europe and Central Asia** for pr7, pr42 are **high**		1
Exports of **most** ECs with *medium REC* to **most** EU countries in **Europe and Central Asia** for pr12, pr13, pr18, pr21, pr26, pr27, pr32, pr33, pr41, pr42 are **low**		0.9
Exports of **most** ECs with *medium REC* to **most** EU countries in **Europe and Central Asia** for pr1, pr2, pr3, pr4, pr5, pr6, pr7, pr8, pr9, pr10, pr11, pr14, pr15, pr16, pr17, pr19, pr20, pr22, pr23, pr24, pr25, pr28, pr29, pr30, pr31, pr34, pr35, pr36, pr37, pr38, pr39, pr40 are **low**		1
Exports of a **few** ECs with *medium REC* to a **few** EU countries in **Europe and Central Asia** for pr5, pr7, pr19, pr20, pr22, pr24, pr25, pr27, pr28, pr30, pr33, pr34, pr35, pr39, pr41 are **medium**		0.9
Exports of a **few** ECs with *medium REC* to a **few** EU countries in **Europe and Central Asia** for pr42 are **high**		1
Exports of a **few** ECs with *medium REC* to a **few** EU countries in **Europe and Central Asia** for pr7 are **high**		0.9
Exports of **most** ECs with *high REC* to **most** EU countries in **Europe and Central Asia** for all products are **low**		1
Exports of a **few** ECs with *high REC* to a **few** EU countries in **Europe and Central Asia** for pr5, pr12, pr19, pr20, pr22, pr24, pr25, pr27, pr28, pr30, pr32, pr33, pr34, pr35, pr39, pr41 are **medium**		0.9
Exports of a **few** ECs with *high REC* to a **few** EU countries in **Europe and Central Asia** for pr7, pr42 are **medium**		1
Exports of a **few** ECs with *high REC* to a **few** EU countries in **Europe and Central Asia** for pr7, pr42 are **high**		1
Exports of **most** ECs with *low REC* to **most** EU countries in the **Middle East and North Africa** for all products are **low**		1
Exports of a **few** ECs with *low REC* to a **few** EU countries in the **Middle East and North Africa** for pr5, pr7, pr19, pr20, pr22, pr24, pr25, pr27, pr28, pr30, pr33, pr34, pr35, pr39, pr41 are **medium**		0.9
Exports of a **few** ECs with *low REC* to a **few** EU countries in the **Middle East and North Africa** for pr7, pr42 are **high**		1
Exports of **most** ECs with *medium REC* to **most** EU countries in the Middle **East and North Africa** for all products are **low**		1
Exports of a **few** ECs with *medium REC* to a **few** EU countries in the **Middle East and North Africa** for pr5, pr7, pr19, pr20, pr22, pr24, pr25, pr27, pr28, pr30, pr33, pr34, pr35, pr39, pr41 are **medium**		0.9
Exports of a **few** ECs with *medium REC* to a **few** EU countries in the **Middle East and North Africa** for pr42 are **high**		1
Exports of a **few** ECs with *medium REC* to a **few** EU countries in the **Middle East and North Africa** for pr7 are **high**		0.9
Exports of **most** ECs with *high REC* to **most** of the EU countries in **Middle East and North Africa** for all products are **low**		1
Exports of a **few** ECs with *high REC* to a **few** the EU countries in the **Middle East and North Africa** for pr5, pr12, pr19, pr20, pr22, pr24, pr25, pr27, pr28, pr30, pr32, pr33, pr34, pr35, pr39, pr41 are **medium**		0.9
Exports of a **few** ECs with *high REC* to a **few** EU countries in the **Middle East and North Africa** for pr7, pr42 are **medium**		1
Exports of a **few** ECs with *high REC* to a **few** EU countries in the **Middle East and North Africa** for pr7, pr42 are **high**		1

pr: product group.

Table 5
Generated LSs for EPI of EC countries and Region of EU countries.

Summaries	T	D
Exports of **most** ECs with *low EPI* to **most** EU countries in **Europe and Central Asia** for all products are **low**		1
Exports of a **few** ECs with *low EPI* to a **few** EU countries in **Europe and Central Asia** for pr5, pr7, pr12, pr19, pr20, pr22, pr24, pr25, pr27, pr28, pr30, pr32, pr33, pr34, pr35, pr39, pr4, pr42 are **medium**		0.9
Exports of a **few** ECs with *low EPI* to a **few** EU countries in **Europe and Central Asia** for pr7, pr42 are **high**		1
Exports of **most** ECs with *medium EPI* to **most** EU countries in **Europe and Central Asia** for pr18, pr21, pr26, pr27, pr32, pr33, pr41, pr42 are **low**		0.9
Exports of **most** ECs with *medium EPI* to **most** EU countries in **Europe and Central Asia** for pr1, pr2, pr3, pr4, pr5, pr6, pr7, pr8, pr9, pr10, pr11, pr12, pr13, pr14, pr15, pr16, pr17, pr19, pr20, pr22, pr23, pr24, pr25, pr28, pr29, pr30, pr31, pr34, pr35, pr36, pr37, pr38, pr39, pr40 are **low**		1
Exports of a **few** ECs with *medium EPI* to a **few** EU countries in **Europe and Central Asia** for pr5, pr7, pr19, pr20, pr22, pr24, pr25, pr27, pr28, pr30, pr32, pr33, pr34, pr35, pr39, pr41 are **medium**		0.9
Exports of a **few** ECs with *medium EPI* to a **few** EU countries in **Europe and Central Asia** for pr7, pr42 are **high**		1
Exports of **most** ECs with *high EPI* to **most** EU countries in **Europe and Central Asia** for pr1, pr2, pr3, pr4, pr5, pr6, pr7, pr8, pr9, pr10, pr11, pr12, pr14, pr15, pr16, pr17, pr19, pr20, pr21, pr22, pr23, pr26, pr27, pr28, pr30, pr32, pr33, pr36, pr38, pr41, pr42 are **low**		0.9
Exports of **most** ECs with *high EPI* to **most** EU countries in **Europe and Central Asia** for pr13, pr18, pr25, pr29, pr24, pr31, pr34, pr35, pr37, pr39, pr40 are **low**		1
Exports of a **few** ECs with *high EPI* to a **few** EU countries in **Europe and Central Asia** for pr5, pr19, pr24, pr25, pr34, pr35, pr39, pr41 are **medium**		0.9
Exports of a **few** ECs with *high EPI* to a **few** EU countries in **Europe and Central Asia** for pr7, pr42 are **high**		1
Exports of **most** ECs with *low EPI* to **most** EU countries in the **Middle East and North Africa** for all products are **low**		1
Exports of a **few** ECs with *low EPI* to a **few** EU countries in the **Middle East and North Africa** for pr5, pr7, pr12, pr19, pr20, pr22, pr24, pr25, pr26, pr27, pr28, pr30, pr33, pr34, pr35, pr39, pr41, pr42 are **medium**		0.9
Exports of a **few** ECs with *low EPI* to a **few** EU countries in the **Middle East and North Africa** for pr7, pr42 are **high**		1
Exports of **most** ECs with *medium EPI* to **most** EU countries in the **Middle East and North Africa** for all products are **low**		1
Exports of a **few** ECs with *medium EPI* to a **few** EU countries in the **Middle East and North Africa** for pr5, pr7, pr12, pr19, pr20, pr22, pr24, pr25, pr27, pr28, pr30, pr32, pr33, pr34, pr35, pr39, pr41 are **medium**		0.9
Exports of a **few** ECs with *medium EPI* to a **few** EU countries in the **Middle East and North Africa** for pr7, pr42 are **high**		1
Exports of **most** ECs with *high EPI* to **most** EU countries in the **Middle East and North Africa** for all products are **low**		1
Exports of a **few** ECs with *high EPI* to a **few** EU countries in the **Middle East and North Africa** for pr5, pr19, pr24, pr25, pr34, pr35, pr39, pr41 are **medium**		0.9
Exports of a **few** ECs with *high EPI* to a **few** EU countries in the **Middle East and North Africa** for pr42 are **high**		0.9

pr: product group.

evident that pr12: Fertilizers; mineral or chemical, nitrogenous are predominantly exported from countries with low EPI scores. Based on the findings, it can be observed that pr26: Screws, bolts, nuts, coach screws, screw hooks, rivets, cotters, cotter-pins, washers, and similar articles of iron or steel were sourced from nations with lower EPI in the Middle East and North Africa, in contrast to Europe and Central Asia.

Table 6 presents LSs obtained through a comparative analysis of the exporting regions of countries, as classified by the World Bank, and the regions of EU countries based on their export volumes. Based on the collected data, it can be observed that nations engaged in the exportation of their products are distributed across various geographical regions. Due to this rationale, synopses were aggregated for nations engaged in export activities across a cumulative count of seven geographical areas. The regions above encompass the following: East Asia and the Pacific, Europe and Central Asia, Latin America and the Caribbean, the Middle East and North Africa, North America, South Asia, and Sub-Saharan Africa.

Comparable findings were observed for the ECs in Latin America and the Caribbean, the Middle East and North Africa, South Asia, and Sub-Saharan Africa. The exports from these countries to EU countries are characterized by notable quantities of exports, particularly in the case of pr7: Electrical energy and pr42: Iron and steel. In contrast to the EU countries in Europe and Central Asia, the EU countries in the Middle East and North Africa exhibit moderate exports, as indicated by the value denoted as pr26: Screws, bolts, nuts, coach screws, screw hooks, rivets, cotters, cotter-pins, washers (including spring washers) and similar articles, of iron or steel. North America exhibits a notable presence in terms of high export volumes, whereas countries in Europe and Central

Table 6
Generated LSs for Regions of EC and EU countries.

Summaries	T D
Exports of **most** ECs in East Asia and Pacific to **most** EU countries in **Europe and Central Asia** for pr1, pr2, pr3, pr4, pr5, pr6, pr7, pr8, pr9, pr10, pr11, pr12, pr13, pr14, pr15, pr16, pr17, pr18, pr19, pr20, pr23, pr24, pr25, pr26, pr28, pr29, pr30, pr31, pr32, pr33, pr34, pr35, pr36, pr37, pr38, pr39, pr40 are **low**	1
Exports of **most** ECs in East Asia and Pacific to **most** EU countries in **Europe and Central Asia** for pr21, pr22, pr27, pr42 are **low**	0.9
Exports of a **few** ECs in East Asia and Pacific to a **few** EU countries in **Europe and Central Asia** for pr5, pr7, pr12, pr19, pr20, pr22, pr24, pr25, pr27, pr28, pr30, pr32, pr33, pr34, pr35, pr39, pr41, pr42 are **medium**	0.9
Exports of a **few** ECs in East Asia and the Pacific to a **few** EU countries in **Europe and Central Asia** for pr7, pr42 are **high**	1
Exports of **most** ECs in East Asia and the Pacific to **most** EU countries in the **Middle East and North Africa** for all products are **low**	1
Exports of a **few** ECs in East Asia and the Pacific to a **few** EU countries in the **Middle East and North Africa** for pr5, pr7, pr12, pr19, pr20, pr22, pr24, pr25, pr27, pr28, pr30, pr32, pr33, pr34, pr35, pr39, pr41, pr42 are **medium**	0.9
Exports of a **few** ECs in East Asia and the Pacific to a **few** EU countries in the **Middle East and North Africa** for pr7, pr42 are **high**	1
Exports of **most** ECs in Europe and Central Asia to **most** EU countries in **Europe and Central Asia** for pr1, pr2, pr3, pr4, pr5, pr6, pr7, pr8, pr9, pr10, pr11, pr14, pr15, pr16, pr17, pr19, pr23, pr24, pr25, pr29, pr31, pr34, pr35, pr37, pr38, pr39, pr40 are **low**	1
Exports of **most** ECs in Europe and Central Asia to **most** EU countries in **Europe and Central Asia** for pr12, pr13, pr18, pr20, pr21, pr22, pr26, pr27, pr28, pr30, pr32, pr33, pr36, pr41, pr42 are **low**	0.9
Exports of a **few** ECs in Europe and Central Asia to a **few** EU countries in **Europe and Central Asia** for pr5, pr19, pr24, pr25, pr34, pr35, pr39, pr41 are **medium**	0.9
Exports of a **few** ECs in Europe and Central Asia to a **few** EU countries in **Europe and Central Asia** for pr42 are **high**	0.9
Exports of **most** ECs in Europe and Central Asia to **most** EU countries in the **Middle East and North Africa** for all products are **low**	1
Exports of a **few** ECs in Europe and Central Asia to a **few** EU countries in the **Middle East and North Africa** for pr5, pr19, pr20, pr24, pr25, pr30, pr34, pr35, pr39, pr41 are **medium**	0.9
Exports of a **few** ECs in Europe and Central Asia to a **few** EU countries in the **Middle East and North Africa** for pr42 are **high**	0.9
Exports of a **few** ECs in North America to a **few** EU countries in **Europe and Central Asia** for pr7, pr24, pr25, pr28, pr34, pr35, pr39 are **medium**	0.9
Exports of the **most** ECs in North America to **most** EU countries in **Europe and Central Asia** for pr1, pr2, pr3, pr4, pr5, pr6, pr7, pr8, pr9, pr10, pr11, pr14, pr15, pr16, pr17, pr19, pr29, pr31, pr34, pr35, pr37, pr39, pr40 are **low**	1
Exports of the **most** ECs in North America to **most** EU countries in **Europe and Central Asia** for pr12, pr13, pr18, pr20, pr21, pr22, pr23, pr24, pr25, pr26, pr27, pr28, pr30, pr32, pr33, pr36, pr38, pr41, pr42 are **low**	0.9
Exports of a **few** ECs in North America to a **few** EU countries in **Europe and Central Asia** for pr7 are **high**	1
Exports of a **few** ECs in North America to a **few** EU countries in the **Middle East and North Africa** for pr7, pr24, pr25, pr28, pr34, pr35, pr39 are **medium**	0.9
Exports of the **most** ECs in North America to **most** EU countries in the **Middle East and North Africa** for pr1, pr2, pr3, pr5, pr6, pr7, pr8, pr9, pr10, pr11, pr12, pr13, pr14, pr15, pr16, pr17, pr18, pr19, pr20, pr21, pr22, pr23, pr24, pr25, pr26, pr27, pr28, pr29, pr30, pr31, pr32, pr33, pr34, pr35, pr36, pr37, pr38, pr39, pr40, pr41, pr42 are **low**	1
Exports of the **most** ECs in North America to **most** EU countries in the **Middle East and North Africa** for pr4 are **low**	0.9
Exports of a **few** ECs in North America to a **few** EU countries in the **Middle East and North Africa** for pr7 are **high**	1
Exports of a **few** ECs in Latin America and the Caribbean to a **few** EU countries in **Europe and Central Asia** for pr5, pr7, pr12, pr19, pr20, pr22, pr24, pr25, pr27, pr28, pr30, pr32, pr33, pr34, pr35, pr39, pr41, pr42 are **medium**	0.9
Exports of the **most** ECs in Latin America and the Caribbean to **most** EU countries in **Europe and Central Asia** for all products are **low**	1
Exports of a **few** ECs in Latin America and the Caribbean to a **few** EU countries in **Europe and Central Asia** for pr7, pr42 are **high**	1
Exports of a **few** ECs in Latin America and the Caribbean to a **few** EU countries in the **Middle East and North Africa** for pr5, pr7, pr12, pr19, pr20, pr22, pr24, pr25, pr26, pr27, pr28, pr30, pr32, pr33, pr34, pr35, pr39, pr41, pr42 are **medium**	0.9
Exports of the **most** ECs in Latin America and the Caribbean to **most** EU countries in the **Middle East and North Africa** for all products are **low**	1

Table 6 (*continued*)

Summaries	T D
Exports of a **few** ECs in Latin America and the Caribbean to a **few** EU countries in the **Middle East and North Africa** for pr7, pr42 are **high**	1
Exports of a **few** ECs in the Middle East and North Africa to a **few** EU countries in **Europe and Central Asia** for pr5, pr7, pr12, pr19, pr20, pr22, pr24, pr25, pr27, pr28, pr30, pr32, pr33, pr34, pr35, pr39, pr41, pr42 are **medium**	0.9
Exports of **most** ECs in the Middle East and North Africa to **most** EU countries in **Europe and Central Asia** for all products are **low**	1
Exports of a **few** ECs in the Middle East and North Africa to a **few** EU countries in **Europe and Central Asia** for pr7, pr42 are **high**	1
Exports of a **few** ECs in the Middle East and North Africa to a **few** EU countries in the **Middle East and North Africa** for pr5, pr7, pr12, pr19, pr20, pr22, pr24, pr25, pr26, pr27, pr28, pr30, pr32, pr33, pr34, pr35, pr39, pr41, pr42 are **medium**	0.9
Exports of **most** ECs in the Middle East and North Africa to **most** EU countries in **the East and North Africa** for all products are **low**	1
Exports of a **few** ECs in the Middle East and North Africa to a **few** EU countries in the **Middle East and North Africa** for pr7, pr42 are **high**	1
Exports of a **few** ECs in South Asia to a **few** EU countries in **Europe and Central Asia** for pr5, pr7, pr12, pr19, pr20, pr22, pr24, pr25, pr27, pr28, pr30, pr32, pr33, pr34, pr35, pr39, pr41, pr42 are **medium**	0.9
Exports of **most** ECs in South Asia to **most** EU countries in **Europe and Central Asia** for all products are **low**	1
Exports of a **few** ECs in South Asia to a **few** EU countries in **Europe and Central Asia** for pr7, pr42 are **high**	1
Exports of a **few** ECs in South Asia to a **few** EU countries in the **Middle East and North Africa** for pr5, pr7, pr12, pr19, pr20, pr22, pr24, pr25, pr26, pr27, pr28, pr30, pr32, pr33, pr34, pr35, pr39, pr41, pr42 are **medium**	0.9
Exports of ECsn South Asia to most EU countries in the **Middle East and North Africa** for all products are **low**	1
Exports of a **few** ECs in South Asia to a **few** EU countries in the **Middle East and North Africa** for pr7, pr42 are **high**	1
Exports of a **few** ECs in SubSaharan Africa to a **few** EU countries in **Europe and Central Asia** for pr5, pr7, pr12, pr19, pr20, pr22, pr24, pr25, pr27, pr28, pr30, pr32, pr33, pr34, pr35, pr39, pr41, pr42 are **medium**	0.9
Exports of **most** ECs in SubSaharan Africa **most** EU countries in **Europe and Central Asia** for all products are **low**	1
Exports of a **few** ECs in SubSaharan Africa to a **few** EU countries in **Europe and Central Asia** for pr7, pr42 are **high**	1
Exports of a **few** ECs in SubSaharan Africa to a **few** EU countries in the **Middle East and North Africa** for pr5, pr7, pr12, pr19, pr20, pr22, pr24, pr25, pr26, pr27, pr28, pr30, pr32, pr33, pr34, pr35, pr39, pr41, pr42 are **medium**	0.9
Exports ECs in SubSaharan Africa to **most** EU countries in the **Middle East and North Africa** for all products are **low**	1
Exports of a **few** ECs in SubSaharan Africa to a **few** EU countries in the **Middle East and North Africa** for pr7, pr42 are **high**	1

pr: product group.

Asia demonstrate a distinct prominence in terms of significant import quantities. Furthermore, the exports of pr4: Cement; portland, other than white, whether or not artificially coloured originating from countries in North America exhibit a lower level than other products. There are notable exports of pr7: Electrical energy, pr24: Aluminium; structures plates, rods, profiles and tubes for structures, pr25: Containers for compressed or liquefied gas, of iron or steel, pr28: Aluminium; unwrought, pr34: Aluminium; tubes and pipes, pr35: Aluminium; tube or pipe fittings, and pr39: Aluminium; containers for compressed or liquefied gas products from several countries in North America to several EU countries within two distinct regions.

Among the ECs in Europe and Central Asia, it is noteworthy that EU countries in this region exhibit moderate export rates for products labeled as pr5: Cement; aluminous (ciment fondu), whether or not coloured or in the form of clinkers, pr19: Tubes, pipes and hollow profiles, seamless, of iron or steel, pr24: Aluminium; structures plates, rods, profiles and tubes for structures, pr25: Containers for compressed or liquefied gas, of iron or steel, pr34: Aluminium; tubes and pipes, pr35: Aluminium; tube or pipe fittings, pr39: Aluminium; containers for compressed or liquefied gas, and pr41: Aluminium.

In the countries of the EU located in the Middle East and North Africa region, the inclusion of pr20: Iron or steel (excluding cast iron); tubes, pipes, and hollow profiles (not seamless) and pr30: Aluminium; bars,

rods and profiles has been observed in these particular products. In contrast to European and Central Asia, the ECs in East Asia and the Pacific region demonstrate moderate exports for pr7: Electrical energy, pr12: Fertilizers; mineral or chemical, nitrogenous, pr20: Iron or steel (excluding cast iron); tubes, pipes, and hollow profiles (not seamless), pr22: Structures of iron or steel and parts thereof; plates, rods, angles, shapes, sections, tubes and the like, prepared for use in structures, pr27: Iron or steel; articles, pr28: Aluminium; unwrought, pr30: Aluminium; bars, rods and profiles, pr32: Aluminium; plates, sheets and strips, thickness exceeding 0.2 mm, pr33: Aluminium foil of a thickness not exceeding 0.2 mm, and pr42: Iron and steel products. Notably, these specific products are primarily exported to the East Asia and Pacific region. The significance of ECs in the Pacific cannot be overstated.

The LSs for each CN code pertaining to REC by ECs were derived. These countries' exports to countries in the EU are broken down into categories according to their EPI and regional affiliations, and these summaries provide insights into those exports. During the implementation of the CBAM, the goal is to determine which product groups are particularly important for each country located within a particular region. In addition, this analysis aims to determine the important product groups for various regions and those specific to each region. Because of the data obtained, decision-makers and policymakers now have significant new insights into the increased vulnerability of various groups to carbon leakage.

4.2. Discussion

Our analysis highlights that, despite the abundance of nation-specific evaluations on CBAM in the literature, there is no thorough worldwide analysis. However, by offering a comprehensive analysis of the broader implications and efficacy of such accords worldwide, our research helps close this gap. LS also adds value to the research by comprehensive overviewing of complex data. By presenting information in natural language, large datasets become more understandable for a wider audience who may not have specialized knowledge in data mining. LS saves time and effort compared to analyzing raw data or lengthy reports. Decision-makers might concentrate attention on particular regions or economic entities that need more research or action by declaring locations with high or low export levels. Complex interdependencies, such as those involving export volumes, economic entities, geographies, and environmental performance measures, can be better understood by decision-makers.

Comparing the results of this study with the literature is not feasible due to the inclusion of analyses for multiple nations in this study. In contrast, the literature primarily focuses on one or a few countries. An in-depth analysis was conducted to investigate the correlations between the findings of the research mentioned in the literature and the outcomes of this particular investigation. Research undertaken in China has indicated that implementing applications like CBAM will lead to a decline in China's exports[7,4]. The sectors experiencing the most significant decline in exports were characterized as energy-intensive and carbon-intensive sectors. The six sectors mentioned are part of the CBAM and corroborate the findings of this study. Moreover, it is projected that that approach will decrease China's carbon emissions. The research undertaken by Kou for Taiwan and Acar for Turkey demonstrated that implementing CBAM will adversely affect the economies of these nations [21,1].

According to Fouré et al. [13], border carbon mechanisms will decrease the import of products with high greenhouse gas emissions. It will increase competitiveness in these markets as ECs seek alternative regions. Additionally, they asserted that Canada and the USA will partially offset the European market's losses. According to Ren et al. [28], China, the rest of Asia and the Pacific, and Russia are projected to be the countries most significantly impacted by the CBAM for plastic products. It was asserted that less developed nations would experience greater losses than developed ones. The results of this study are directly correlated with the low EPI levels observed in less developed countries. Based on the research conducted by Zhong and Pei [41], there is a projected rise in EU output soon, while production in other parts of the world is expected to decline. Due to distinct regional peculiarities, China, Russia, and India were forecasted to bear the greatest burden.

The prevailing consensus in the literature suggests that implementing a carbon tariff will have profound ramifications on the global economy, aligning with the findings of this study. The adoption of low-carbon economies and technology is crucial and urgent for nations. Additional recommendations for countries include capitalizing on the opportunities presented by the domestic market and adopting localized carbon pricing methods [28,7,4,41,21].

This study set out with the aim of assessing the exports of 42 product groups between EC and EU countries in different aspects: export level (low, medium, high), regions, REC (low, medium, high), and EPI (low, medium, high). Diverse results were seen at different levels of the analysis. These distinctions in the outcomes highlight how intricate and varied the interactions under study are. They draw attention to the complex interactions between export levels, regional dynamics, patterns of use of renewable energy, and environmental performance metrics. This shows that a thorough understanding of the interconnections between these variables is necessary to create policies and programs that effectively promote sustainable development and reduce environmental deterioration. In the following, the outcomes were broken down further based on EPI levels, REC levels, export levels and regional dynamics.

4.2.1. EPI levels

The majority of exports from EC countries with low EPI to the majority of EU nations in the Middle East, North Africa, and Central Asia are low, with a few notable exceptions that indicate a medium- or high-rated exports for particular product categories such as cement, aluminuim, electrical energy. While there are occasional medium-rated exports for particular product groups such as iron or steel, aluminium, cement, and electrical energy, the majority of exports from EC countries with medium EPI to the majority of EU countries in Europe, Central Asia, the Middle East, and North Africa are low. Most EU countries in Europe, Central Asia, the Middle East, and North Africa receive low-rated exports from ECs with high EPIs, with a small number of high-rated exports seen for particular product categories, which are electrical energy, iron and steel and destinations.

With a few exceptions that show medium-rated exports, especially for certain product categories such as cement, iron and steel, aluminium, and high-rated exports for specific product groups like electrical energy, iron and steel, most EU countries with high EPI exports are primarily low across a range of product groups (except iron and steel) from most EC countries with low REC.

4.2.2. REC levels

Exports from the majority of EC countries with low REC are low, especially for certain product groups such as fertilizers, aluminium, and screws, to EU nations with high EPI. However, medium-rated exports are noted for a few EC countries, with few exceptions, such as cement, aluminium, and tubes. With a few notable outliers where medium-rated exports are noted, particularly for nearly product groupings (except from aluminium, iron and steel), EC countries with medium REC primarily exhibit low exports to most EU nations in Europe and Central Asia. Except for a few medium-rated exports for particular product groups such as cement, tubes, iron, steel, and aluminium and a few cases where exports are medium to high for particular EC countries, most EC countries with high REC show poor exports to EU nations in Europe and Central Asia.

4.2.3. Export levels

The results were analyzed in depth according to the export levels. In summary, low exports are between most EC countries with low REC and most EU countries with low EPI. As for the medium export levels, we

conclude that some EC countries with medium REC in different regions export products to a few EU countries with medium EPI. Lastly, some EC countries with high REC, particularly in regions like North America, Latin America, the Middle East, and North America, have high export levels for specific products to a few EU countries with high EPI.

4.2.4. Regional dynamics

Most exports are low, while pr7: Electrical energy and pr42: Iron and steel exports are high from East Asia and the Pacific to Europe, Central Asia, the Middle East, and North Africa. Most exports are low from Europe and Central Asia to the Middle East and North Africa except pr42: Iron and steel. From North America, pr7: Electrical energy exports are high to Europe and Central Asia, while pr7: Electrical energy exports are medium to Middle East and North Africa. From Latin America, the Caribbean, South Asia, and Sub-Saharan Africa countries, most of the exports are low, the exports of electrical energy, iron and steel to Europe and Central Asia are high, electrical energy, iron and steel to the Middle East and North Africa are medium. From the Middle East and North Africa electrical energy, iron and steel exports are high.

5. Conclusion

The objective of this study was to propose a robust framework for applying the LS approach in analyzing the exports of countries that engage in trade with EU member states before the implementation of the CBAM transition phase, scheduled to commence in October 2023. The process of exporting data pertaining to countries entails the establishment of a highly complex network, necessitating the utilization of several approaches to enhance the comprehensibility of this data. Within this framework, the 42 CN codes encompassed in the CBAM transition period were regarded as a dataset showing export countries. Simultaneously, additional factors such as the EPI, regional affiliation, and REC were employed to provide further assessment of the countries' circumstances. LSs encompass their inclusion to enhance comprehension.

This paper offers a thorough examination of the transitional phase of the CBAM, revealing the extensive scope of its impact on numerous countries. This outcome indicates that nearly every country is impacted by the CBAM. Nevertheless, it is essential to highlight that when the volume of exports grows, there is a corresponding reduction in the number of CN codes and ECs impacted by the CBAM. Based on the findings obtained, it is evident that the goods pr7: Electrical energy and pr42: Iron and steel are the most significantly impacted. This finding suggests that implementing CBAM should prioritize particular product categories and provide due consideration to these categories.

This study offers a thorough comprehension of intricate dynamics by considering both the trade flows between countries and the unique attributes of each country. Through an analysis of the product groups encompassed by CBAM, which is still in its early stages, in conjunction with LS, it has been determined which product groups pose a significant danger for ECs and the imperative need for carbon reduction strategies. It supplied input data for EU countries to be used in incentive systems by disclosing the present status of product groups, countries, and regions. This study offers decision-makers and policymakers valuable insights for the transition period of the CBAM. Additionally, it showcases the successful application of the LS approach in analyzing intricate data.

The limitations of this study arise primarily from the uncertainty in the data, which can affect the accuracy of the results and the credibility of the research. Through the power of fuzzy set theory, uncertainty is modeled, and its impact on the results is successfully reduced. Another limitation is about CN codes in the data set. The CN codes in the data set are previously classified, preventing us from more detailed categorization.

In forthcoming research endeavors, the advancement of CBAM and LS methodology can be facilitated by using several approaches. These approaches encompass the identification of significant product categories specific to each country, the generation of LSs, and the provision of further summary information. Furthermore, the present study can be broadened by incorporating variables about the commercial interactions between nations, such as trade agreements, commercial cooperation, customs agreements, and trade balance. Country characteristics can be enhanced by incorporating variables such as investments in green technology, developing carbon-free transportation infrastructure, and implementing environmental taxes.

CRediT authorship contribution statement

Fatma Şener Fidan: Conceptualization, Methodology, Writing – original draft, Data curation, Formal analysis, Resources, Validation. **Sena Aydoğan:** Conceptualization, Data curation, Methodology, Writing – original draft. **Diyar Akay:** Investigation, Methodology, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

We have added all our data to the supplemantary Document

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.aei.2024.102528.

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