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Mapping the landscape of carbon accounting research in Southeast Asia: A bibliometric analysis

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Abstract:

Carbon accounting plays a pivotal role in both national and corporate responsibility for mitigating carbon emissions associated with manufacturing and supply chain management. Considering the rapid economic growth of Southeast Asian countries and its consequent impacts on climate change, this bibliometric study aims to comprehensively capture the research landscape of carbon accounting in the region. Publications from 2013 to 2023 were retrieved from the Scopus database. Bibliometric analysis of publication numbers, citations, journals, and network mapping of countries and keywords was conducted using Microsoft Excel 365, VOSviewer 1.6.20, and RStudio. In total, 5,883 publications were included in the final analysis, with the number of articles steadily increasing over time. Singapore and Malaysia emerged as the two countries with the largest publication output and the highest citation counts. Singapore, Malaysia, and Indonesia also formed the most active collaboration network. Recent research trends on carbon accounting in ASEAN highlight chemistry and materials science within the manufacturing sector, while the social science aspects of data management have received less attention. In the future, ASEAN countries should strengthen mutual cooperation and place greater emphasis on the quality of emission data, the impacts of energy consumption in the region, and the potential applications of machine learning in data management.

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1. Introduction

The increasing urgency of addressing climate change has spurred the development of carbon accounting as a critical tool for measuring and managing greenhouse gas (GHG) emissions. The concept of carbon accounting began to receive attention from researchers in the early 2000s. Early works by scholars such as N.H. Ravindranath, et al. (2008) [1] defined carbon accounting as the quantification of CO_2 emissions from various sources and carbon capture within forest ecosystems. Following this, J. Bebbington, et al. (2008) [2] emphasised the role of carbon accounting in corporate social responsibility and sustainability reporting, underscoring the importance of transparent and accurate mechanisms for accountability and improved environmental performance. A more comprehensive framework was later introduced by K. Stechemesser, et al. (2012) [3], who expanded the definition of carbon accounting to encompass both monetary and non-monetary evaluation of carbon-related assets. This includes the monitoring of GHG emissions across value chains and the assessment of ecosystem carbon cycles. Such an approach demonstrates the complex nature of carbon accounting, integrating financial and environmental dimensions to address the multifaceted challenges of climate change mitigation.

Unlike traditional financial accounting, which focuses solely on managing and reporting an organisation's economic activities, carbon accounting integrates financial and non-financial dimensions to address corporate environmental performance, making its definition more complex [3]. As a subset of environmental accounting, its financial aspect concerns environment-related financial data, such as investments in green technologies and associated profits, waste management costs, or expenses for research and development. Meanwhile, the non-financial aspect relates to an organisation's tactical approaches in controlling carbon emissions and research innovations in material inputs and outputs. With increasing societal and environmental concerns over time, the conceptual evolution of carbon accounting changes from measuring CO_2 emissions and carbon storage in biomass (2007) [1], to the estimation and removal of GHG emissions

on a global scale (2012) [4], and, more recently, to the measuring, monitoring, reporting, and verification of GHG levels across supply chains and product life cycles (2023) [5]. These progressive transformations emphasise the crucial role of carbon accounting at both organisational and national levels in fulfilling the mission of carbon neutrality.

There are several reasons why carbon accounting is challenging in practice. First, based on its more recent unified definition, carbon accounting is regarded as the management of carbon emissions throughout a product's life cycle, rather than being confined to the manufacturing process. This requires consolidated efforts across various research disciplines such as environmental engineering, energy innovation, and economics [6]. Second, as carbon emissions must be measured and reported by all organisations involved in the supply chain, critical questions arise concerning carbon accounting responsibility [6]. In particular, clarifying emission liabilities between supplier and consumer nations in inter-regional cargo transportation remains a significant challenge. Third, to enable comprehensive tracking and disclosure of carbon emission sources and carbon capture, corporations often face resource constraints in implementing carbon accounting techniques, as well as limited expertise and financial incentives [7]. Moreover, incorporating carbon assessments into every stage of a product's life cycle is especially challenging in developing countries and among emerging businesses, where technology, skilled human resources, and operational budgets remain pressing issues. In summary, carbon accounting has become a benchmark for businesses and countries to demonstrate active engagement in environmental preservation, which is essential in addressing the current climate crisis. It plays a pivotal role in accurately allocating carbon allowances to all parties within supply chains and in evaluating both organisational and national sustainability commitments.

Carbon accounting has garnered increasing attention in Southeast Asia (ASEAN) in recent years. Balancing economic growth with the mitigation of global warming is undoubtedly a global challenge - one not limited to large economies such as the United States and China, but increasingly relevant to emerging economies. This is especially the case in ASEAN, which is projected to outpace China in gross domestic product (GDP) and foreign direct investment (FDI) growth over the next decade (2024-2034)

[8]. Economic development in the region has long been associated with environmental degradation, largely due to carbon emissions from industrial expansion and energy consumption [9]. According to the International Energy Agency (IEA), carbon emissions from the Indochinese peninsula (Cambodia, Laos, Thailand, Myanmar, and Vietnam) surged by 60% between 2008 and 2018, mainly driven by economic growth [10]. Coal usage has increased significantly in Laos, Vietnam, and Cambodia, with Laos showing the highest dependence at 61.8% in 2017 [9]. Similarly, Q. Munir, et al. (2020) [11] noted the heavy reliance of economic growth in the Philippines and Singapore on fossil fuels. J.B. Ang (2008) [12] also identified a causal relationship between output growth and pollutant emissions in Malaysia. Carbon management is particularly challenging in Southeast Asian countries, given weak environmental regulations - such as coal price subsidies in Laos and Vietnam - or a lack of environmental consideration in the private sector [9, 13]. Given these challenges, providing a holistic overview of carbon accounting literature in ASEAN is essential for understanding existing research patterns on emissions and for developing carbon reduction strategies suited to rapidly developing economies.

Bibliometric analysis has become widely used in academia as a tool to systematically map the current research status of a field of study and to identify future research directions. It was first defined by W.G. Potter (1981) [14] as “the study and measurement of the publication patterns of all forms of written communication and their authors”. Since then, the method has been well developed and increasingly applied across a wide range of disciplines, spanning from business and management [15, 16] to public health and medicine [17, 18]. By providing a comprehensive overview of research developments, bibliometric analysis enables researchers to quickly and effectively understand the current research landscape, as well as to identify critical gaps that pave the way for future studies. Unlike traditional literature reviews and systematic reviews, bibliometric analysis offers a quantitative, data-driven overview of a research field [19]. While conventional reviewing approaches deliver in-depth qualitative insights, they often focus on narrowly defined research questions with a limited number of papers. Bibliometric analysis complements these approaches by synthesising literature evidence from a macro-level perspective. This quantitative technique applies

numerical analyses and statistical methods to authors, journals, institutions, and keywords extracted from scientific articles, thereby mapping the intellectual, social, and conceptual structure of a research discipline. By revealing emerging trends and the evolution of a field, bibliometric analysis equips researchers with a broader perspective to guide future scholarly work - whether for conducting literature reviews to support theoretical development or for performing systematic reviews and meta-analyses on specific topics.

Although numerous bibliometric studies have been conducted on carbon accounting, the novelty of this research lies in its specific focus on the ASEAN region. For example, K. Kuriawan, et al. (2022) [20] performed a bibliometric analysis of carbon accounting research from 2012 to 2021 without regional restrictions. Their study predicted significant growth in research themes related to carbon accounting, reflecting increasing awareness among industrial companies of their environmental impacts and their responsibility for reporting GHG emissions. By contrast, Y. Zheng, et al. (2022) [21] provided a critical review of carbon accounting in social science-related studies between 1997 and 2020. Their results emphasised the need for more carbon reduction actions at the organisational level and recommended additional empirical research on responsibility allocation from a consumption perspective. Another scientometric study by Y. Du, et al. (2024) [6] focused specifically on responsibility accounting, while R. Kaur, et al. (2023) [7] reviewed conceptual developments in carbon accounting and offered practical implications for developing a standardised framework that integrates carbon accounting into manufacturing systems and supply chains. Collectively, these bibliometric analyses highlight significant advancements in the scientific understanding of carbon accounting and motivate the present study to provide a structured review of developments in Southeast Asia. By considering the distinctive developmental pace of ASEAN countries as transitioning economies, this review provides useful insights for shaping future carbon accounting research agendas in the region, which is vital to achieve long-term goals of mitigating global warming.

Previous studies on carbon accounting in ASEAN countries have largely focused on specific topics in isolation, leaving a gap in comprehensive assessments of the field. Existing research has primarily examined carbon emissions, emission drivers, carbon

ecosystems, and the integration of corporate and natural climate solutions. Notably, recent studies have highlighted rapid carbon emission growth in the region, driven primarily by economic expansion, with biomass and coal as the dominant sources [9, 22, 23]. For instance, in Thailand, improvements in energy efficiency have been linked to a partial slowdown in emission growth [11]. Southeast Asia is also recognised as a global hotspot for organic carbon storage, hosting extensive mangrove and seagrass ecosystems [24-26]. Indonesia possesses vast mangrove areas, where preservation and restoration are critical for maintaining carbon stocks and mitigating emissions. Other strands of research have explored corporate carbon accounting, which faces challenges in integrating natural climate solutions [27, 28], and consumption-based carbon accounting, which shows household consumption as a major emission source - particularly in Malaysia, Singapore, and Thailand [29]. While these studies provide valuable insights into individual aspects of carbon accounting in ASEAN, no comprehensive review has yet synthesised research developments and identified emerging themes. This underscores the need for a holistic assessment of carbon accounting in ASEAN that considers its diverse dimensions from a sustainability perspective.

The novelty of this study is that it represents the first bibliometric review conducted to track research developments in carbon accounting within Southeast Asian countries. This research contributes to the existing literature in at least three ways: (1) by identifying the current research status of ASEAN carbon accounting through bibliometric indicators such as publications, citations, and country-level collaboration; (2) by determining research hotspots using a mix of analytical tools, including VOSviewer and RStudio, to enhance reproducibility; and (3) by providing guidance for future research directions related to carbon accounting in the region. By processing the increasing volume of ASEAN-focused publications, this bibliometric analysis identifies key themes and emerging areas, thereby guiding the knowledge base and informing both research and policymaking.

This study addresses four research questions (RQs):

RQ1: What is the current status of ASEAN carbon accounting research (e.g., growth rate, journal contributions)?

RQ2: What is the role of country interconnection in influencing ASEAN carbon accounting research?

RQ3: What are the common topics and emerging themes in the field?

RQ4: What are the future implications for ASEAN carbon accounting research?

The findings of this study have practical implications for strengthening environmental responsibility and sustainability initiatives in ASEAN. Results show that research productivity is largely concentrated in Singapore and Malaysia. Strengthening collaborative research across ASEAN should therefore be a priority to reinforce regional commitments to environmental preservation. Furthermore, the findings support future research on carbon data management and provide policy-relevant insights into mitigating the environmental impacts of economic growth, energy consumption, and deforestation. This bibliometric analysis also highlights the potential applications of artificial intelligence and machine learning in carbon accounting, which are likely to become critical research domains in the future.

The remainder of this paper is structured as follows: first, a review of the conceptual progression of carbon accounting is provided, followed by a description of the methodology employed. Results and discussion are then presented, and finally, the paper concludes with key findings and recommendations for future research and policy.

2. Methodology

2.1. Data source and search strategy

To conduct this bibliometric analysis, we employed Scopus, one of the most widely used databases for scholarly publications. Alongside the Web of Science Core Collection (WoS), Scopus is recognised as an optimal database for scientometric studies. It provides a large volume of publications across multiple disciplines and a comprehensive set of metadata for each document, which can be readily extracted and analysed using reference management software and other analytical tools.

There is no single “best” database for bibliometric analysis [30]. While WoS - established in 1964 - is the oldest scholarly database and is noted for its rigorous journal selection and coverage, Scopus is recognised for its broader journal inclusion, particularly in the humanities and social sciences, as well as for its utility in interdisciplinary research and research visualisation [31]. Given that approximately

99.11% of journals indexed in WoS are also covered in Scopus [31], the use of either database is justifiable for data collection in bibliometric studies.

The search strategy comprised three stages:

First, we executed a search query using the following keywords: “greenhouse gas”, “carbon”, “CO_2”, “carbon dioxide”, “accounting”, “calculation”, and “measurement”. These keywords were adapted from a systematic review on carbon accounting [3] and a bibliometric analysis of carbon emissions [6], ensuring alignment of this scientometric study with existing research while focusing specifically on the Asian region. Boolean operators (AND/OR) were applied to the Topic search function (Title, Abstract, and Keywords). The full search string was: TITLE-ABS-KEY (“greenhouse gas” OR “carbon” OR “CO_2” OR “carbon dioxide” OR “greenhouse gas emissions”) AND TITLE-ABS-KEY (“account*” OR “calculation” OR “measurement”). The total number of papers yielded was 458,258.

Second, various filtering processes were applied to refine the relevancy of publications. Since the search was performed in May 2024, papers published between January and May 2024 may not fully represent annual research trends. We therefore limited the dataset to a 10-year period (2013-2023) to comprehensively capture developments in carbon accounting research. In addition, we restricted the sample to publications written in English and classified as research articles, excluding reviews, books, book chapters, and other document types.

Finally, country filtering was applied to include only publications affiliated with Southeast Asian countries: Brunei Darussalam, Myanmar, Cambodia, Indonesia, Laos, Malaysia, the Philippines, Singapore, Thailand, and Vietnam.

In summary, the inclusion criteria were:

Publication year: between 2013 and 2023;

Language: English;

Document type: Research articles;

Country/territory: ASEAN countries.

The final dataset comprised 5,883 publications. All three steps of the search process were independently conducted by two researchers, followed by a detailed

review of the extracted information and a consensus on the final selection. Each publication was retrieved in full record format.

2.2. Data analysis

In this study, bibliometric analysis was applied to identify research trends in carbon accounting in Southeast Asian countries.

For descriptive statistics, we analysed the following indicators: number of publications by year, citation counts, and publication distribution by journal, affiliation, country, and research area. Data on articles specifically within the field of Economics were also obtained, along with the most impactful publications in this category. These analyses were conducted using Microsoft Excel 365. To generate mapping graphs of by-country collaboration networks and keyword co-occurrences, we used VOSviewer software (version 1.6.20). VOSviewer is extensively utilised in bibliometric analysis to visually reflect collaboration patterns between authors, organisations, and countries [30, 32, 33]. It is also commonly used to analyse the links between keywords repeatedly cited in articles.

In addition, RStudio software was utilised to examine the temporal growth of research themes, which is essential for identifying emerging trends and research gaps in the field. RStudio is widely employed in bibliometric studies [20, 34], as it enables the analysis of bibliometric indicators and thematic developments from unstructured scientific data [35].

A summary of data extraction and analysis is presented in Fig. 1.

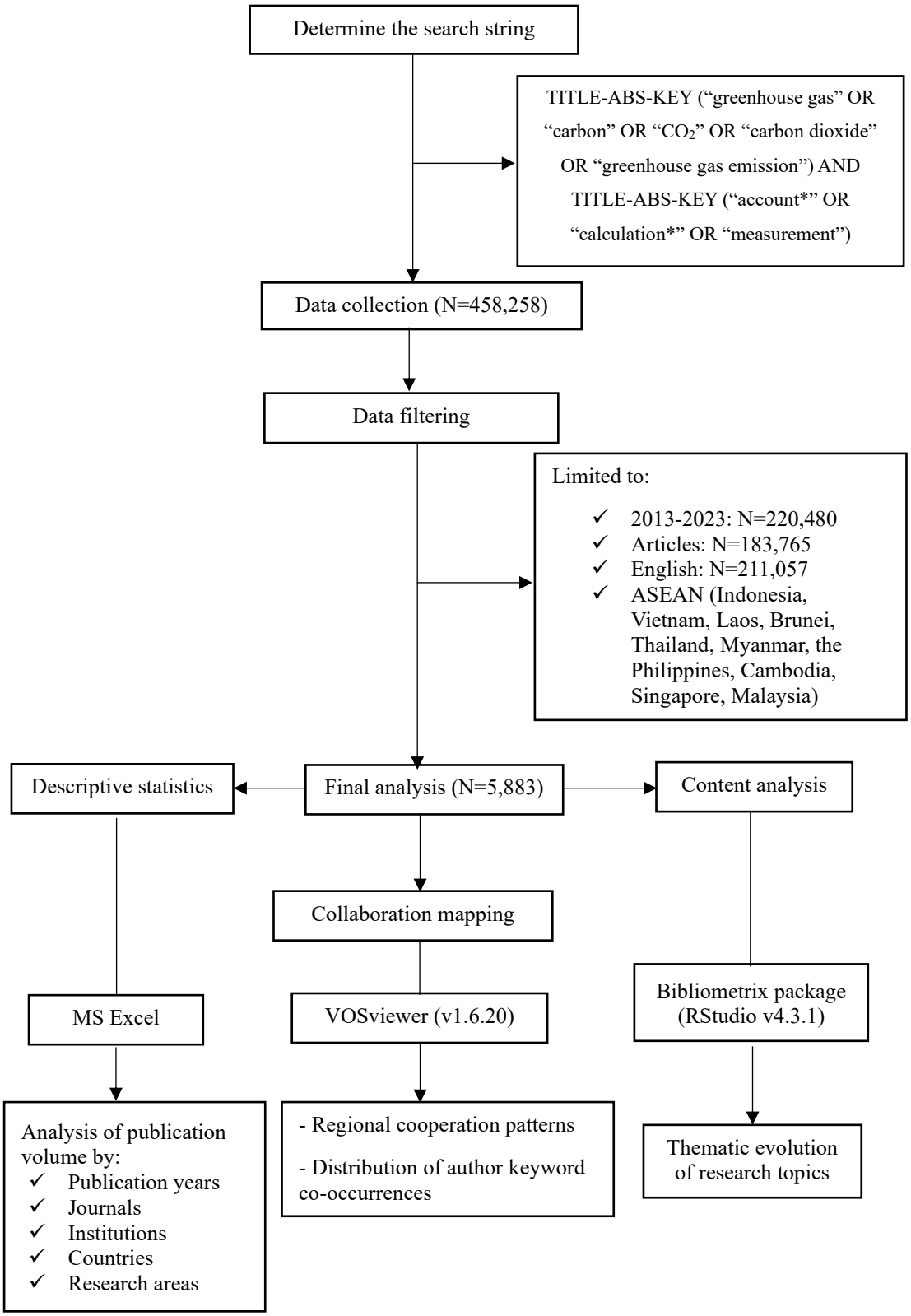

Fig. 1. Flow diagram of bibliometric analysis. Source: Authors' research results.

3. Results

3.1. Analysis of publication output

Figure 2 illustrates the variation in the number of publications over the 10-year period. A total of 5,883 publications were included in the final analysis, with the majority appearing in the past five years. The number of publications increased steadily, from 279 articles in 2013 to 840 articles in 2023 - almost tripling the initial level. The most substantial increase occurred between 2013 and 2019.

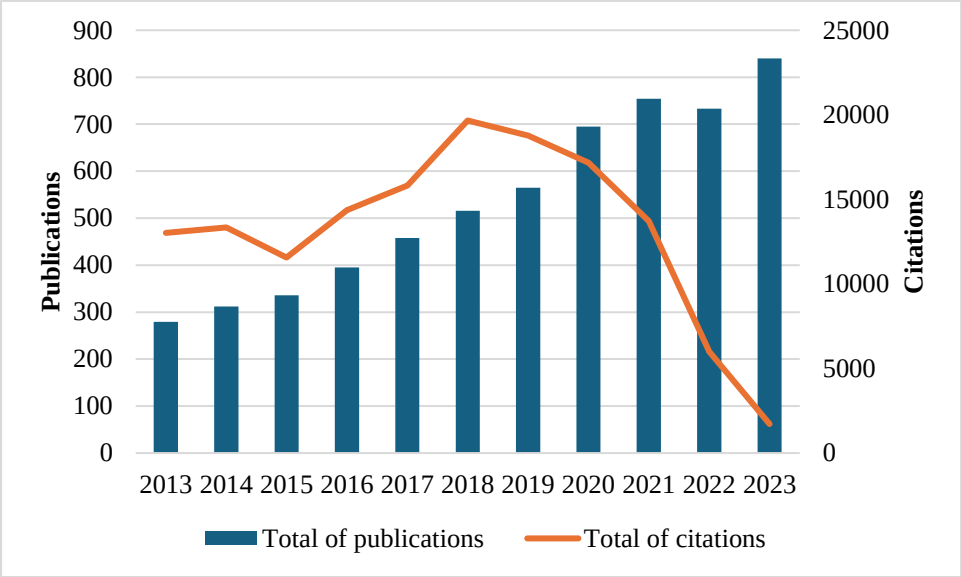

Fig. 2. Number of publications and citations from 2013 to 2023. Source: Authors' research results.

As shown in Fig. 2, total citations of carbon accounting-related articles also followed a strong upward trend from 2013 to 2021, before declining in 2022 and 2023. Annual citations stood at 13,025 in 2013, peaked at 19,663 in 2018, and then decreased slightly to 13,720 in 2021.

3.2. Analysis of journals

Figures 3 and 4 present the journals with the highest numbers of publications and citations, respectively. As shown in Fig. 3, the top three journals publishing the most articles related to carbon accounting in Southeast Asia are Chemical Engineering Transactions, RSC Advances, and Applied Surface Science, each with an average of 50 publications. By contrast, Fig. 4 highlights the journals with the highest citation counts in this field, including Nature Communications, Advanced Functional Materials, and Angewandte Chemie - International Edition, each with at least 3,000 citations. These

results indicate clear differences between the journals with the greatest number of publications and those with the greatest citation impact.

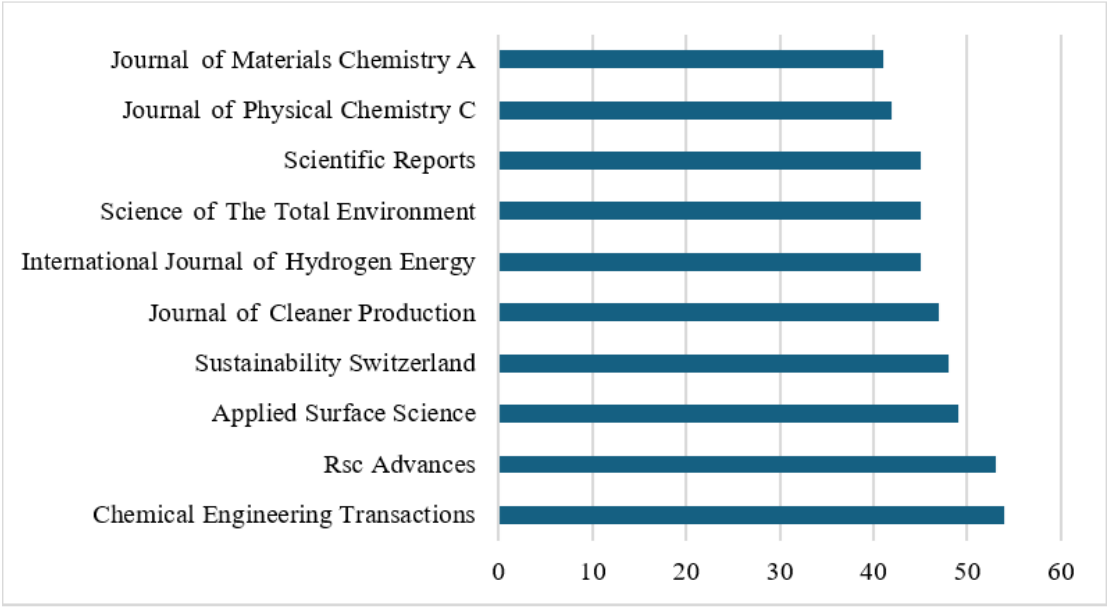

Fig. 3. Top 10 journals with the highest publications. Source: Authors' research results.

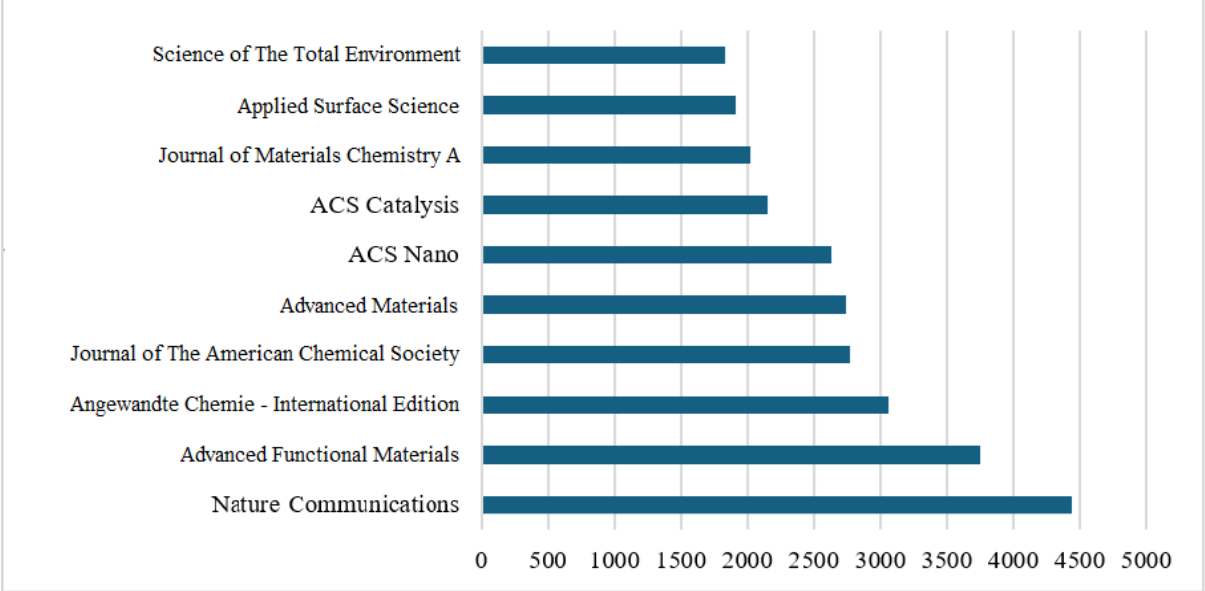

Fig. 4. Top 10 journals with the highest citations. Source: Authors' research results.

3.3. Analysis of institutions

Figure 5 presents the top 10 institutions with the highest number of publications across ASEAN countries. Malaysia holds the leading position in terms of the number of organisations contributing a large volume of research, with five of the top 10 institutions located there, including the University of Malaya, which ranked third. It is also

noteworthy that four of the 10 most active educational institutions in carbon accounting research are based in Singapore. The National University of Singapore was the highest-ranking university overall, with 635 publications during the 10-year period, followed by Nanyang Technological University, also in Singapore. In addition to Malaysian and Singaporean institutions, several Indonesian organisations appeared in the top 10, alongside one Thai institution: Chulalongkorn University, which recorded 167 publications.

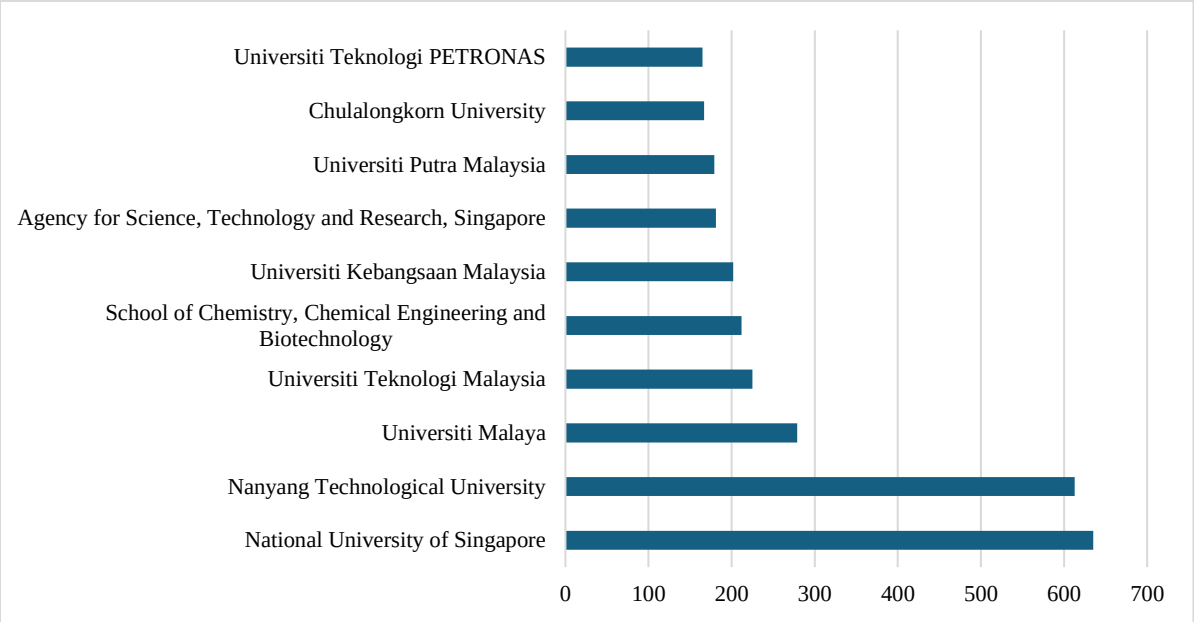

Fig. 5. Top 10 institutions with the highest publications. Source: Authors' research results.

3.4. Analysis of countries

Figure 6 compares the number of publications and citations across Southeast Asian countries in descending order. Malaysia holds the leading position in terms of publication output, with more than 1,600 articles published between 2013 and 2023. However, Singapore records the highest number of citations - almost double Malaysia's figure. Following these two are Thailand, Indonesia, Vietnam, and the Philippines, which rank among the most active ASEAN countries in carbon accounting research output. In terms of citations, the middle-ranking countries are Thailand, Vietnam, Indonesia, and the Philippines. By contrast, the remaining four countries - Brunei Darussalam, Cambodia, Laos, and Myanmar - have produced the smallest volume of carbon accounting-related research and have also received the fewest citations.

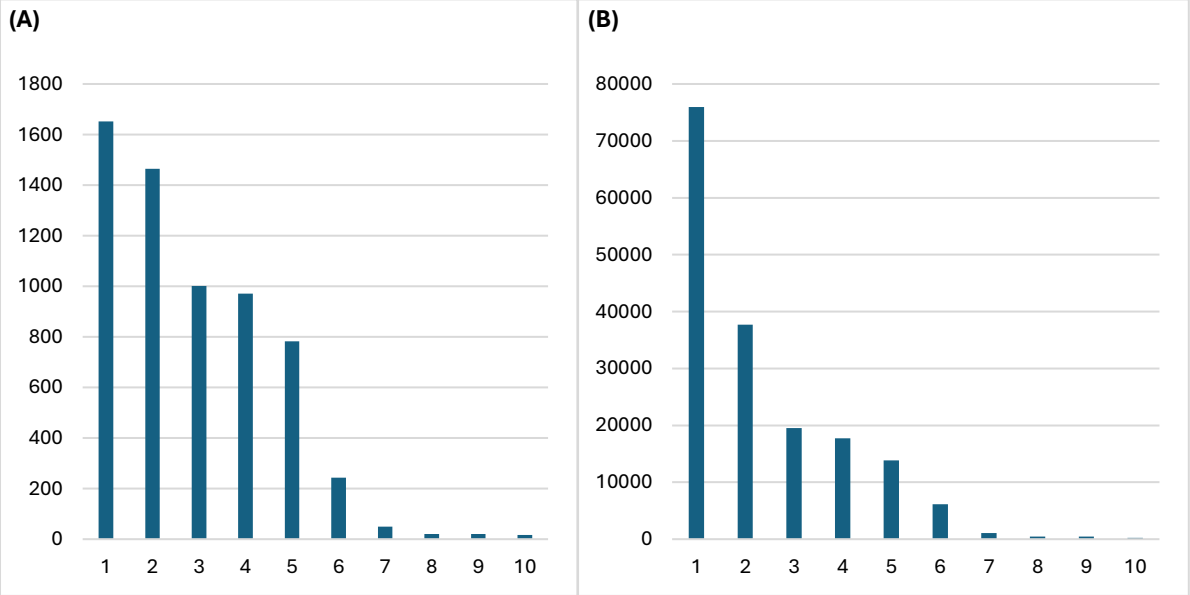

Fig. 6. Number of publications (A) and citations (B) by country. Source: Authors' research results.

3.5. Analysis of research areas

Figure 7 presents the 10 most prominent research areas in the field of carbon accounting. The most common topics fall within the natural sciences, with Chemistry (14%), Materials Science (13%), Engineering (12%), Environmental Science (10%), and Chemical Engineering (9%) accounting for the largest shares.

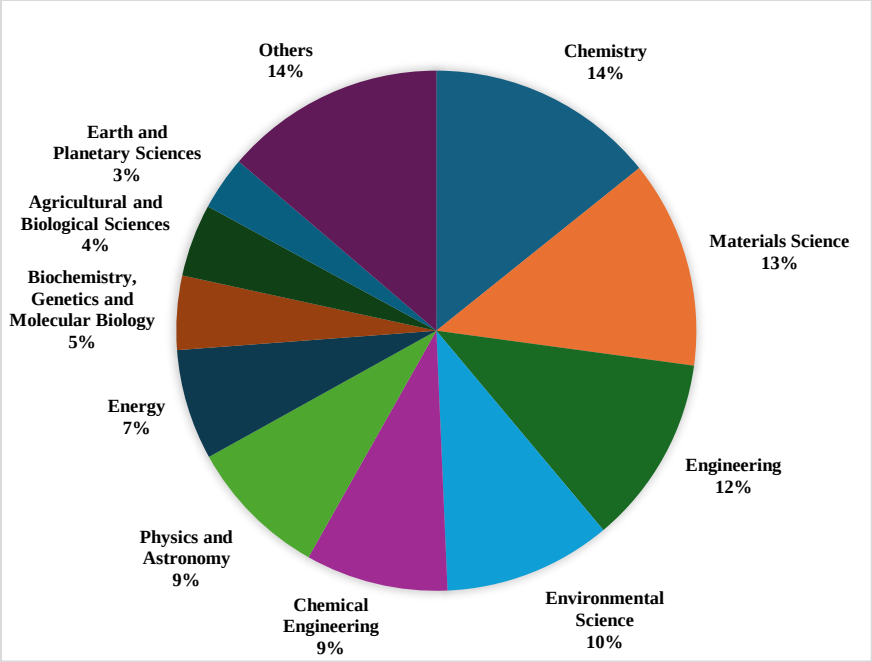

Fig. 7. Share of publications (%) by research areas. Source: Authors' research results.

3.6. Analysis of country collaboration

To aid interpretation of the VOSviewer graphs, a circle represents a particular term being analysed, such as an author, institution, country, or keyword. Based on the data networking algorithm, terms are distributed into colour-coded clusters. The larger the circle, the more frequently the term appears in the dataset; the closer the circles are to one another, the stronger their connections. The thickness of each line indicates the strength of the relationship between terms.

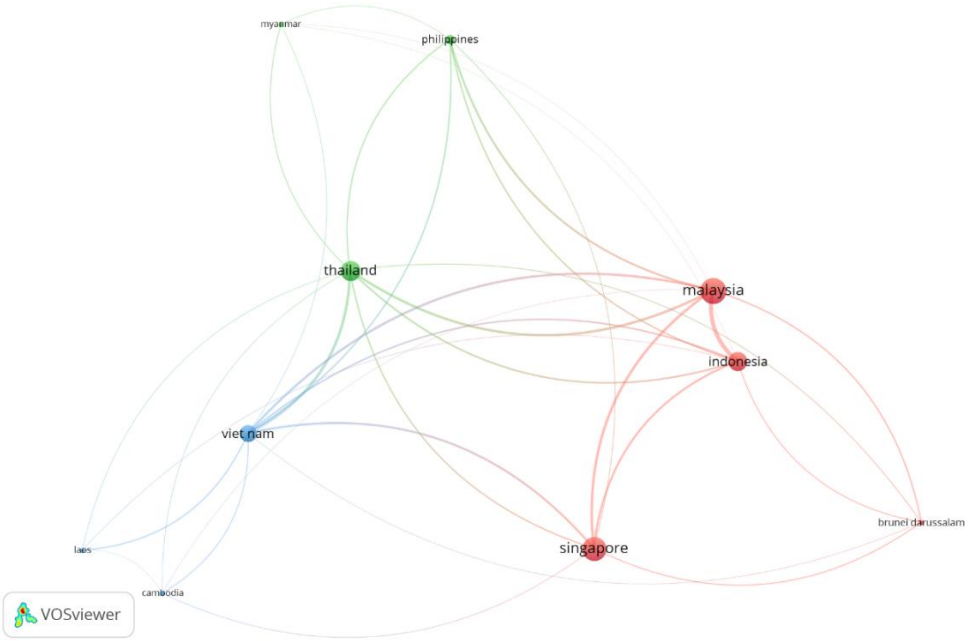

Fig. 8. Network visualization of cooperations among ASEAN countries. Source: Authors' research results.

Figure 8 depicts the collaborative networks of Southeast Asian countries in carbon accounting research from 2013 to 2023. Three major clusters are identified: a red cluster (Malaysia, Indonesia, Singapore, and Brunei Darussalam), a green cluster (Thailand, the Philippines, and Myanmar), and a blue cluster (Vietnam, Laos, and Cambodia). These clusters were formed according to the link strengths of collaboration among countries. Notably, the representatives of each cluster are Singapore, Thailand, and Vietnam. Malaysia and Singapore emerged as the most productive countries in carbon accounting research and also received the highest citation counts over the 10-year period. Prominent collaboration networks include Malaysia-Singapore and Malaysia-Indonesia.

3.7. Analysis of keyword co-occurrences

Figure 9 illustrates the keyword co-occurrence clusters from carbon accounting research in ASEAN countries over the 10-year period. Using VOSviewer's word-mapping algorithm to analyse keywords in the titles and abstracts of each publication, only those appearing at least 30 times were included in the analysis. Of the 129,122 keywords identified, 896 met this threshold, resulting in the formation of three major clusters (red, green, and blue).

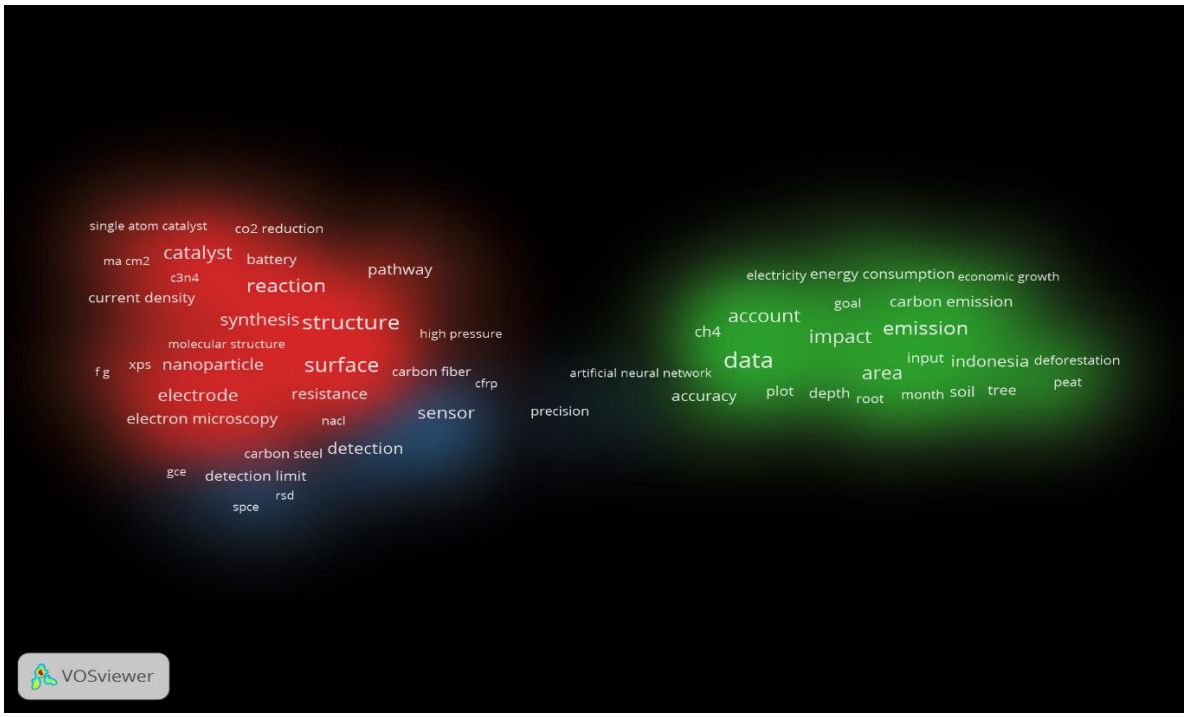

Fig. 9. Cluster density of keywork co-occurrences in ASEAN's carbon accounting research. Source: Authors' research results.

Visualised as the most common research keywords, Cluster 1 (red) reflects natural science developments in the field, particularly chemical engineering and materials science advancements focused on developing optimal materials for carbon mitigation and energy conservation. Cluster 2 (green), the second largest cluster, comprises social science-related keywords such as "data", "impact", "emission", and "deforestation". This cluster centres on carbon emission assessments linked to consumption and economic growth, along with their corresponding regional impacts. Cluster 3 (blue) involves keywords related to viable techniques for carbon detection, such as "detection" and "sensor".

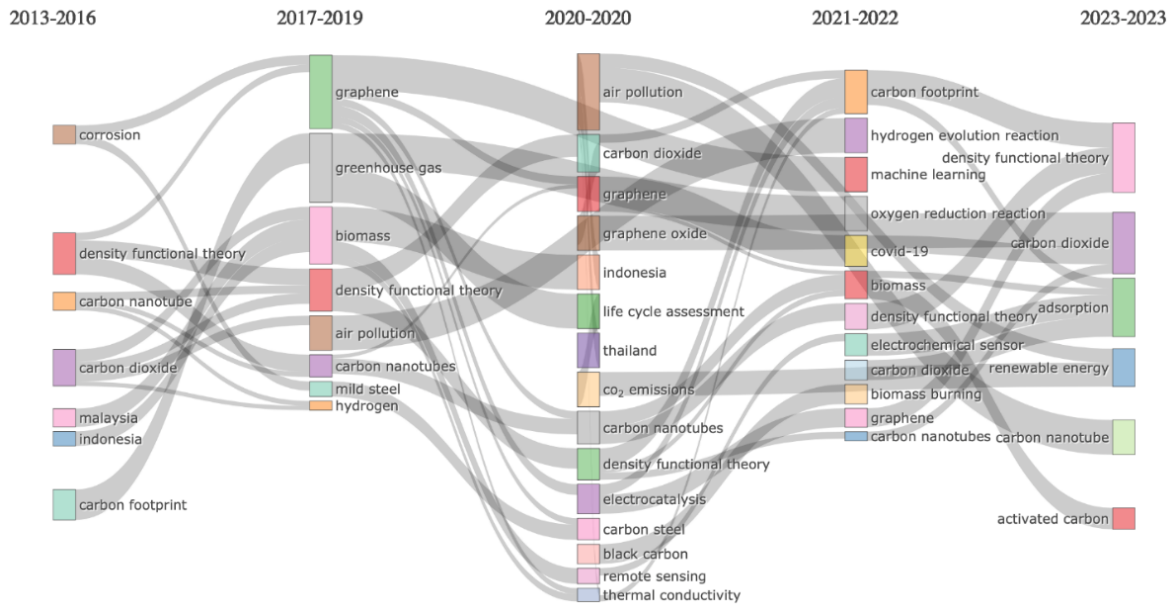

Fig. 10. Thematic evolution of ASEAN's carbon accounting research. Source: Authors' research results.

Figure 10 depicts the thematic evolution of carbon accounting research papers within the ASEAN region. The diagram was generated using the Biblioshiny package in RStudio. To clearly present trends, the 10-year review period was divided into five sub-periods: 2013-2016, 2017-2019, 2020, 2021-2022, and 2023. Each column in the figure is segmented into widely researched topics, with the size of each segment corresponding to the prevalence of that theme. Certain topics remained consistently prevalent throughout the review period, including "density functional theory", "graphene", "carbon nanotube", "biomass", and "carbon footprint". These align with transformative advancements in materials science, environmental science, and related fields aimed at sustainability engineering [36]. Density functional theory - a widely used method by physicists and chemists to study the structure of matter systems (e.g., atoms, molecules, solids) - has become a cornerstone across multiple scientific disciplines, ranging from energy storage and harvesting to molecular engineering and environmental protection [37]. This approach has been extensively applied to carbon-based nanomaterials, yielding results with both high accuracy and reproducibility.

4. Discussion

This section discusses the main findings of the study in relation to the four research questions (RQs):

1. What is the current status of ASEAN's carbon accounting research from (such as growth rate, journal contributions)?

2. What is the role of country interconnection in influencing ASEAN's carbon accounting research?

3. What are the common topics and emerging themes in the field?

4. What are the future implications in ASEAN's carbon accounting research?

To answer RQ1, the current status of carbon accounting research in Southeast Asia can be described as progressive. In terms of growth, although there was a slight decline of approximately 3% in 2021-2022, publication output recovered substantially in 2023, increasing by 15% to reach a peak of 840 articles. This trend aligns with Y. Du, et al. (2024) [6], who identified 2010-2017 as the preliminary development stage of carbon emission accounting publications, followed by 2018-2022 as a period of rapid development characterised by significant progress in the field. Citation analysis revealed that the most impactful articles were published between 2017 and 2020, which recorded the highest citation counts. Although citations have shown a slight downward trend since 2022, the steady rise in publication numbers underscores sustained scholarly interest in carbon accounting.

Regarding journal analysis, we found that among the top 10 journals with the largest volumes of publications, three - Applied Surface Science, Science of the Total Environment, and Journal of Materials Chemistry A - were also among the most frequently cited. One probable reason for their higher publication and citation counts is their broad interdisciplinary scope, which attracts submissions from multiple fields and appeals to a diverse readership. For example, Applied Surface Science and Journal of Materials Chemistry A publish across wide-ranging areas of materials science, physics, and chemistry, while Science of the Total Environment covers topics including sustainability, environmental science, ecology, pollution, and policy. Another reason is that these journals publish a high volume of articles annually and frequently feature trending topics beyond carbon accounting - such as carbon capture, nanomaterials, and

renewable energy - that typically attract more citations and contribute to strong citation networks.

To answer RQ2, the analysis of university and country performance indicates strong contributions and collaborations in the field of carbon accounting across the region. Singapore, Malaysia, and Thailand, together with their leading universities, take the lead in terms of both research output and influence. This is consistent with the findings of N.M. Aris, et al. (2024) [38], which highlight these countries' strong performance in carbon management research. Their higher publication counts reflect a greater emphasis on research and development in this area. Specifically, Singapore became the first ASEAN member to introduce a carbon tax in 2019 [39]; Malaysia has made substantial investments in sustainability, renewable energy, and climate mitigation research through policies such as the Green Technology Master Plan and the Malaysia Green Transition [40]; and Thailand established the Thailand Greenhouse Gas Management Organization in 2008 to support GHG-related research and initiatives [41]. These policy frameworks and funding commitments have created fertile ground for research capacity and resources, enabling universities in these countries to foster productive and impactful research environments that advance carbon accounting studies. In addition, strong collaboration networks - such as those between Singapore and Malaysia, and between Vietnam, Laos, and Cambodia - can be partly attributed to geographical proximity, which facilitates joint research activities and regional knowledge exchange.

In response to RQ3, common topics in ASEAN carbon accounting are primarily situated within the natural sciences, particularly materials development, energy sources, and agricultural sciences. The emphasis on biochemistry and materials science reflects industrial priorities to design environmentally sustainable production systems. Carbon emissions arise mainly from two sources: energy demand and embedded carbon in materials across their life cycle, from production to disposal [42]. Alongside measuring direct emissions of carbon dioxide and other greenhouse gases from energy production and consumption, it is equally important to estimate the indirect emissions embedded in materials used for industrial activities. Identifying carbon values in different materials and resources enables evaluation of the total carbon output of production

processes and supports carbon footprint management at the organisational level. Consequently, materials and chemicals with a low carbon footprint that are easily reused or recycled are increasingly preferred by industries seeking environmental sustainability. These innovations in energy use and materials development play a pivotal role in reducing overall carbon emissions and advancing sustainable industrial practices [6].

Our findings are consistent with previous studies showing that natural sciences dominate the carbon accounting research landscape compared with other fields [3, 6, 21]. Carbon accounting is a complex, multidimensional concept that varies according to disciplinary perspective [20, 43]. Broadly, it can be divided into two themes: non-financial and financial aspects, corresponding to the physical and social sciences, respectively [3]. Within the natural sciences, most research emphasises advancing carbon quantification in materials used during production and distribution processes, improving energy efficiency, developing renewable energy technologies, designing carbon capture materials, and addressing waste management and air emissions. By contrast, social science research places greater focus on financial reporting of environmental expenditures, strategic planning, evaluation of emission responsibility, corporate social responsibility, and life cycle costing [3]. Y. Zheng, et al. (2020) [21] further note that natural science research in carbon accounting is primarily concerned with improving the accuracy of carbon measurement, whereas social science research concentrates on developing equitable accounting standards.

Furthermore, our findings highlight research gaps in areas such as “carbon data”, “data accuracy”, “energy consumption”, and “economic growth”. Keywords in Cluster 2 (the smaller green cluster) reflect a growing need to improve the reliability and availability of data for carbon accounting. Mitigating carbon footprints requires effective resource management strategies for complex supply chains that extend across national borders. However, the absence of standardised measurements for carbon input-output, together with the lack of practical frameworks for carbon tracing systems throughout product life cycles, continues to hinder companies from producing comprehensive reports on carbon emissions within global trade flows [7]. Accordingly, ASEAN-based research is encouraged to refine existing carbon accounting tools to enhance the quality of emissions data and generate empirical results on carbon

accounting practices. Beyond addressing data transparency and accuracy issues, ASEAN countries should also promote research related to the carbon footprint associated with energy consumption and deforestation.

Changes in research trends over time, emerging themes include “machine learning”, “remote sensing”, and “life cycle assessment”. During the 2013-2016 period, research predominantly focused on topics such as “corrosion”, “density functional theory”, “carbon nanotube”, and “carbon dioxide”, with a significant number of studies originating from Malaysia and Indonesia. Between 2017 and 2019, attention gradually shifted towards material developments, including “graphene”, “hydrogen”, “mild steel”, and “biomass”, which hold promise for energy and environmental applications. In 2020, new terms gained prominence, such as “life cycle assessment”, “electrocatalysis”, “remote sensing”, and “thermal conductivity”. This reflects a growing focus on carbon sequestration technologies alongside greenhouse gas reduction strategies. Remote sensing has become increasingly popular as a reliable and cost-effective method for estimating carbon sequestration in biomass and calculating carbon stocks in land and forestry ecosystems - such as mangroves, seagrass meadows, and tidal marshes - using data gathered from satellites, aircraft, or vessels [44]. Similarly, thermal conductivity has attracted interest as a foundational concept for incorporating earth materials into sustainable building processes [45]. The emergence of life cycle assessment highlights the need for a more comprehensive evaluation of carbon emissions throughout supply chains [7]. In summary, while natural science themes - particularly material development, energy innovation, and environmental science - dominated ASEAN carbon accounting research over the past decade, recent years (2021-2023) have witnessed a notable upsurge in machine learning applications. With rapid advances in artificial intelligence, machine learning now offers a state-of-the-art framework for evaluating carbon footprints [46]. These models address practical business challenges by aggregating and analysing complex emissions data, thereby helping to navigate the intricate landscape of carbon quantification in product logistics from suppliers to consumers.

In response to RQ4, this bibliometric analysis offers practical research and policy implications for ASEAN’s carbon accounting. Regarding research implications, while

carbon accounting research in Southeast Asia has been heavily concentrated in biochemistry and materials sciences, relatively limited attention to social science perspectives creates a significant knowledge gap. First, expanding research in areas such as data standardisation, forest conservation, and the socio-economic drivers of carbon emissions is essential to capture the multifaceted nature of carbon accounting in the ASEAN context. Second, the emergence of themes such as remote sensing, life cycle assessment, and machine learning presents valuable opportunities for integrating advanced technologies with region-specific environmental and economic conditions. Harnessing these methods could improve data transparency and enable more accurate emissions assessments across Southeast Asian supply chains. Third, future research should provide in-depth systematic reviews of these emerging themes to thoroughly map the research landscape and identify specific approaches to carbon accounting practices.

Regarding policy implications, the findings highlight the need to balance technological innovation with governance strategies that are tailored to regional conditions. Recent ASEAN-based studies have increasingly emphasised remote sensing, life cycle assessment, and machine learning. These advancements offer improved methods for monitoring ecosystem carbon stocks and managing emissions throughout product life cycles. Machine learning algorithms, in particular, have been shown to be highly effective in developing remote sensing models, which remain one of the most feasible approaches for calculating carbon values in forest biomass and tracking forest degradation [47, 48]. Accordingly, investments should prioritise the development of simplified, standardised tools for managing complex carbon data, thereby enabling consistent measurement and reporting across ASEAN member states. Moreover, fostering cross-border collaborations in applying AI and machine learning for environmental monitoring could strengthen the region’s collective capacity to track emissions, prevent deforestation, and manage carbon values in manufacturing and supply chains. Such coordinated efforts would not only improve data accuracy and comparability but also reinforce ASEAN’s position in global climate governance and sustainable economic development.

Our findings should be interpreted with certain limitations. First, this study relied exclusively on literature indexed in Scopus, which may limit generalisability due to the potential exclusion of relevant studies from other bibliometric databases. Nonetheless, Scopus is widely recognised as one of the largest curated research databases globally, offering rigorous content evaluation and advanced profiling across a broad range of scientific disciplines and journals [49]. This ensures a high level of representativeness for the present review. Second, although our analysis identified emerging research keywords, further studies are needed to investigate latent research topics in greater detail and to provide deeper qualitative insights into each theme, for example through systematic reviews. Such investigations would help to identify specific areas of carbon accounting that warrant closer scholarly attention in the future.

5. Conclusions

This bibliometric study highlights a substantial increase in carbon accounting research across the 10 ASEAN countries between 2013 and 2023. The steady rise in publications reflects the region's growing commitment to addressing climate change and reducing carbon emissions. Singapore and Malaysia emerged as the leading contributors in terms of both research productivity and collaboration. To mitigate the carbon footprint associated with global trade flows, stronger cross-border collaboration among ASEAN countries is essential. Such cooperation can foster the exchange of knowledge, resources, and best practices, thereby advancing sustainable development in the region. Our findings also show that existing literature on carbon accounting has primarily emphasised sustainable materials, energy storage innovations, and carbon sequestration technologies. Looking ahead, future research and policy efforts should place greater emphasis on the social science dimensions of carbon accounting, including improving data accuracy, implementing effective deforestation countermeasures, and enhancing the integration of artificial intelligence and machine learning into carbon management across manufacturing and supply chain systems.

CRediT author statement

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COMPETING INTERESTS

The authors declare that there is no conflict of interest regarding the publication of this article.

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