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GREEN WAREHOUSING AND SUSTAINABILITY IN THE CONTEXT OF THE ENERGY TRANSITION: A BIBLIOMETRIC ANALYSIS AND LITERATURE REVIEW

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ABSTRACT: This paper presents a bibliometric analysis and literature review of green warehousing (GW) within the context of sustainability and the energy transition. This study analyses 95 peer-reviewed publications from Scopus (2007–2024) to examine research trends, key themes, and methodological approaches. Using VOSviewer, the study identifies major clusters around energy efficiency, consumption, optimisation, and renewable energy use. Interest in GW has increased significantly since 2015, particularly in engineering and computer science, with substantial contributions from Italy, China, and India. While quantitative optimisation dominates, integrating decision-support tools, life cycle assessments, and interdisciplinary methods remains limited. Social science engagement is also lacking. The review calls for more empirical, practice-based research on warehouse technologies and intelligent energy systems within circular and green supply chain models. This study addresses a key gap by linking GW to energy-focused sustainability and offers a replicable framework to guide future research in the global green transition.

KEYWORDS: green warehousing, sustainability, energy transition, bibliometric analysis, literature review

Introduction

Sustainability has attracted widespread academic attention recently, with researchers examining it across various disciplines and practical fields. Current studies focus not only on its theoretical foundations but also on how sustainability principles are being applied in real-world economic practices. This research is closely linked to the broader green transition, which seeks to minimise the environmental impact of economic activity through low-emission and resource-efficient solutions (Kozar & Wodnicka, 2024).

Warehousing and logistics are increasingly at the forefront of the green transition. As key components of modern supply chains, warehouses significantly impact environmental and business performance. Green warehousing (GW), the planning, construction, and management of warehouses with environmental sustainability in mind, has attracted growing academic attention (Bartolini et al., 2019). Once primarily linked to corporate image and social responsibility, GW is now recognised for its economic advantages, such as energy efficiency and cost savings. This shift aligns with EU policy goals promoting low-carbon infrastructure and greener operational practices.

However, the concept of GW remains broad and loosely defined. It includes energy optimisation, emissions reduction, and sustainable facility management. Recent literature often places GW within the larger context of sustainability and logistics, examining its ties to energy use, facility design, and eco-certification. The European energy transition, emphasising efficiency and renewables, has further elevated GW as a relevant study area. Individual EU countries are introducing financial and regulatory support mechanisms to encourage the development of GW.

This study presents a bibliometric analysis and literature review at the intersection of sustainability, energy, and GW. It has two main objectives: (1) to uncover key research themes and their development over time, and (2) to position GW into the broader debate on greening logistics and supply chain infrastructure. The study uses data from the Scopus database and applies a reproducible methodology. Bibliometric maps were generated using VOSviewer (version 1.6.20). The research tracks publication trends and categorises the key characteristics of the literature. The article outlines the methodology, findings, limitations, and future research directions, offering a clear foundation for continued exploration of GW's strategic role in sustainable logistics.

An overview of the literature

Green warehousing (GW) has recently gained growing interest among researchers, reflected in a rising number of publications in scientific journals. Early studies focused primarily on environmental aspects within warehouse management. Over time, energy-related themes became increasingly prominent. These studies began to highlight both environmental benefits and economic gains, as companies realised that implementing green solutions, such as reducing electricity and water use or thermo-modernising buildings, could lead to significant cost savings. Additionally, as consumers became more environmentally conscious, adopting pro-environmental practices also started to offer marketing and public relations advantages.

Bibliometric analysis has revealed diverse applications in the GW field. For instance, Chinese researchers have examined the development of energy regeneration in storage facilities and emphasised the role of emerging energy technologies (Chen et al., 2024). A study from the Politecnico di Milano explored scenarios such as heating system electrification and material-handling equipment (MHE) charging strategies, evaluating both environmental and economic impacts, supported by a sensitivity analysis (Cannava et al., 2024). Similarly, López-Montero et al. (2024) applied control theory to optimise photovoltaic panels and refrigeration systems, offering an example of how automation can enhance warehouse environmental performance.

Numerous publications also use modelling and quantitative methods to assess how green practices affect warehouse operations and financial outcomes. Notable contributions include works by Chiang (2024), Lei (2024), Li et al. (2024), Sandra et al. (2024), and Bhandigani et al. (2024). Another significant study by Oloruntobi et al. (2023) reviewed GW solutions in the context of the UN Sustainable Development Goals (SDGs). The authors examined challenges in meeting environmental targets, warehouse configurations, and green building regulations across the EU, the US, and Asia. Other researchers addressing environmentally friendly warehousing include Ries et al. (2017), Cosma et al. (2024), McLay et al. (2024), and Akandere (2017).

Energy efficiency remains a key focus. Studies by Lv et al. (2022), Pham et al. (2019), and Jensen (2016) highlight how minimising energy use benefits both the environment and business performance. At the same time, emissions from warehousing activities have drawn attention from international bodies and scholars, with works by Daniel and Dissanayake (2021), Md Mashud et al. (2021), and Mashud et al. (2022) addressing this issue. A standout example is the 2023 analysis of Arvato's warehouses, which used performance indicators, automation levels, and categorisation systems to rank warehouse modules based on energy efficiency. The findings challenged the assumption that greater automation leads to better sustainability outcomes. Finally, while most GW-related studies in Scopus focus on technical solutions, notable work can also be found outside major databases. For example, Luu's (2016) thesis on IKEA's warehouses in Finland provides valuable insight into GW implementation in practice.

Research methods

The research, conducted between 2024 and 2025, employed a multi-stage methodological approach that combined bibliometric analysis and literature review to explore the intersection of GW, energy, and sustainability. The methodology followed guidelines by Snyder (2019), Bartolini et al. (2019), and Kozar and Wodnicka (2024), with a strong emphasis on transparency and replicability. The process unfolded in four stages:

1. Initial Review and Research Gap Identification

A preliminary review was conducted using Scopus, Web of Science, and Google Scholar. This revealed a growing body of literature on sustainability in logistics but highlighted a gap in bibliometric research specifically focused on GW and its role in the energy transition, confirming the study's relevance.

2. Conceptual Framework and Keyword Selection

The research design combined a Systematic Literature Review (SLR) to identify trends and a Classic Literature Review (CLR) to capture broader green themes. Author keywords were used as proxies for thematic focus (Aveyard, 2014). Building on Ries et al. (2017) and Bartolini et al. (2019), the search string was defined as:

(sustain*) AND (warehous*) AND (energy)

Searches were limited to English-language, peer-reviewed articles, reviews, book chapters, and conference papers, with no restriction on publication year.

3. Data Collection and Screening

The Scopus search returned 360 documents from 1994 to 2024. A two-stage filtering process was applied. First, only peer-reviewed journal and conference papers from 2007 to 2024 were retained (n = 259), using the following refined query:

(TITLE-ABS-KEY (sustain*) AND TITLE-ABS-KEY (warehous*) AND TITLE-ABS-KEY (energy)) AND PUBYEAR > 2006 AND PUBYEAR < 2025 AND (LIMIT-TO (LANGUAGE, "English")) AND (LIMIT-TO (DOCTYPE, "ar") OR LIMIT-TO (DOCTYPE, "cp")) AND (LIMIT-TO (PUBSTAGE, "final"))

The 2007–2024 timeframe was selected due to a noticeable rise in GW-related publications starting in 2007 and to exclude incomplete annual data for 2025. After abstract screening, 118 papers remained. Another 23 papers were excluded during full-text screening due to lack of relevance or absence of required keywords, leaving a final sample of 95 publications.

4. Data Analysis and Visualisation

Author keywords (n = 483) were extracted, cleaned, and standardised (e.g., spelling, plural forms, typos), resulting in 360 unique keywords. VOSviewer 1.6.20 was used to generate bibliometric maps showing keyword co-occurrence, author collaboration, and citation networks. Metadata was also organised in Microsoft Excel™ for descriptive statistical analysis.

This mixed-method approach enabled a detailed exploration of thematic patterns, key research clusters, and gaps in the literature linking GW with energy and sustainability.

Results of the research

Publication Trends

The publication trend of the selected 95 articles on GW is depicted in Fig. 1. The first relevant paper by Dukić et al. was published in 2010. Over two consecutive years, there were no relevant publications on this topic. The year 2015 marked a significant breakthrough, with seven papers published. Since 2015, 96% of the studies have been published. Furthermore, most publications (25 papers) on GW appeared in 2024, indicating that it is a relatively young field of research. The substantial increase in publications between 2015 and 2024 can be attributed to the heightened focus on integrating environmental sustainability and logistics operations, prompting entrepreneurs to address the carbon footprint of warehouse facilities. A slight reduction in the number of presentations published on GW, with an additional focus on the energy transition, can be observed between 2019 and 2021. This may be attributed to a shift in the focus of researchers towards topics related to the SARS-CoV-2 pandemic. After that time, the number of articles published has shown a steady upward trend. In the last three years, more than half of the works published since 2010 have appeared.

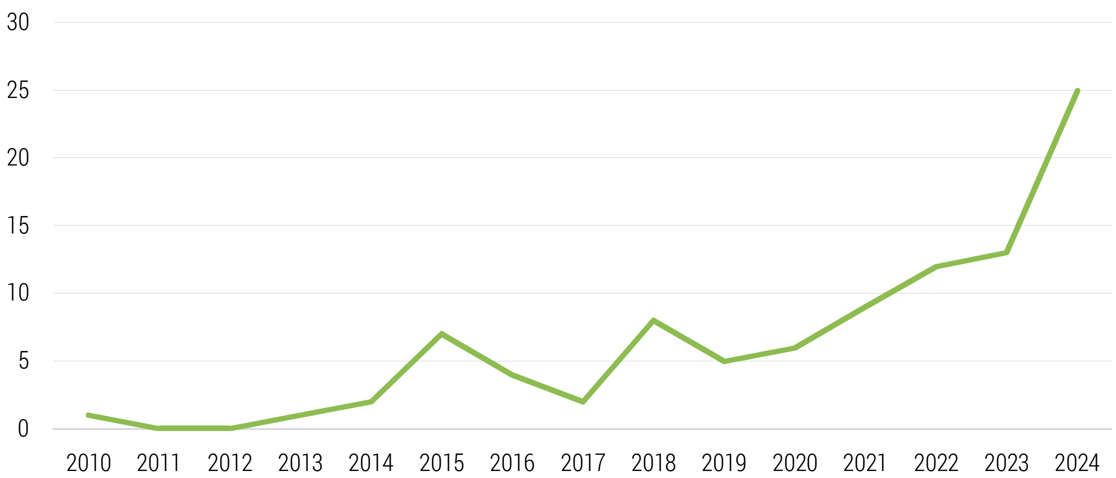

Figure 1. Number of publications on GW per year

Source: authors' work based on www.scopus.com [08-05-2025].

Type of Publications

About 61% of the sample publications are articles in scientific journals, with 64% published after 2020. In general, analysed papers concentrate on two main subject areas, engineering (57%) and computer science (38%), with a relatively smaller number of publications limited to energy (29%), environmental science (29%), business, management and accounting (28%), decision sciences (27%), social sciences (20%) or mathematics (12%). If the research sample is restricted to articles, multiple studies have been published in as few as 11 journals. More than three studies have been published in the *Sustainability (Switzerland), Journal of Cleaner Production,* and *International Journal of Production Research.*

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Author Contributions and International Collaboration

Table 1 shows the number of authors per paper. Most studies (31.6%) were written by three authors, followed by four authors (15.8%) and five authors (15.8%). Among 291 authors contributing to the GW literature, only 29 (about 10%) wrote more than one article in this subject area. Sara Perotti has written ten papers, Antonella Maneghetti – five, and Luca Cannava, Salvatore Digiesi, Francesco Facchini, and Giorgio Mossa – four.

Table 1. Authorships per paper

Authorship	Frequency	Per cent (%)
Single author	6	6.3
Two authors	14	14.7
Three authors	30	31.6
Four authors	15	15.8
Five authors	15	15.8
Six authors	10	10.5
> six authors	5	5.3
Total	95	100

Source: authors' work based on www.scopus.com [08-05-2025].

Authors who have published on GW come from 39 countries. The total strength of co-authorship links with other countries was calculated for each of these 39 countries. Considering the number of published documents and citations, India, the UK, Taiwan, and Italy have the greatest total link strength. Italy and China have published the most papers on this subject (30 and 16 documents, respectively). Authors from Italy, Taiwan, Indonesia, and China also have the most significant number of citations.

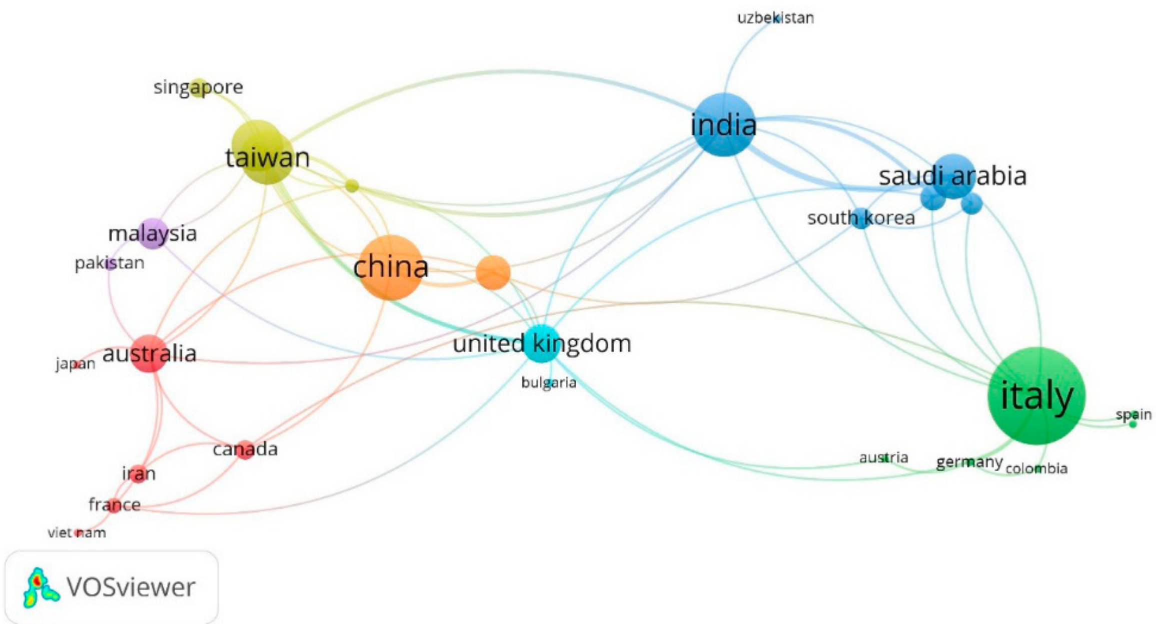

Figure 2. Cooperation links and strengths among different countries

Source: authors' work based on www.scopus.com [10-05-2025].

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In Figure 2, the international cooperation network based on the authors' origin is presented using VOSviewer. Each node represents a country, with its size indicating the number of normalised citations. This normalisation accounts for the fact that older documents may have had more time to receive citations than more recent ones. Papers contributed by authors from Italy, China, and India received the highest number of normalised citations. The links in Figure 2 represent cooperation among countries, with the thickness of each link indicating the strength of collaboration between the two countries. We may distinguish seven clusters in Figure 2. For example, researchers from the UK, India, and Italy have formed the most extensive international collaboration network. In contrast, authors from Benin, Chile, Croatia, Greece, Kazakhstan, the Netherlands, and Poland have not participated in international cooperation and are therefore not represented in the collaboration map above.

Keyword Analysis and Co-occurrence

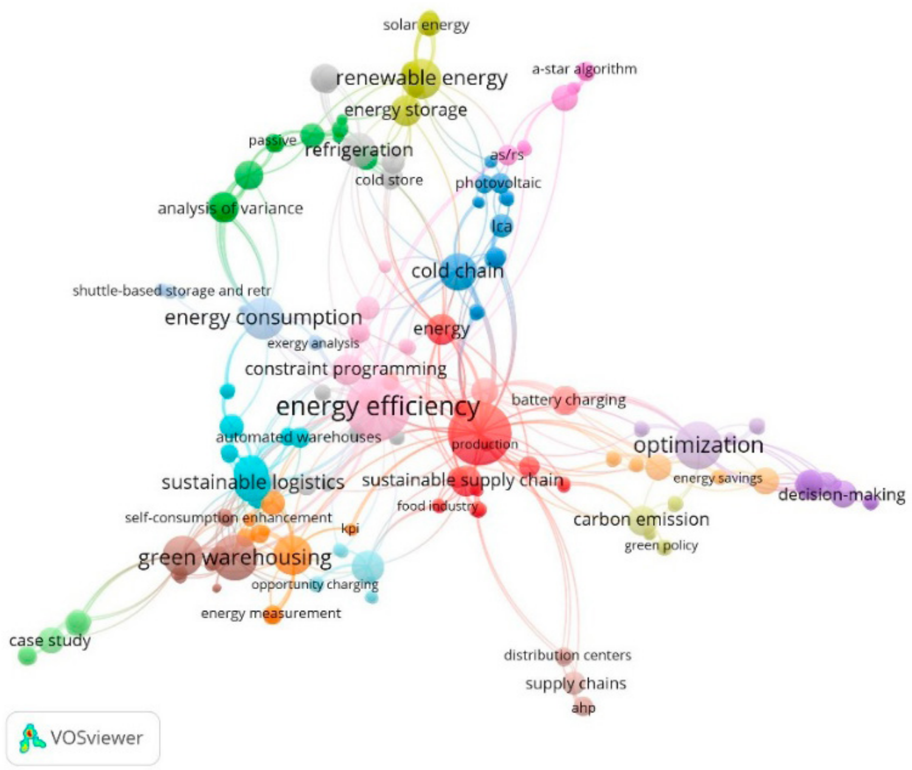
As mentioned before, in the 95 papers, 483 keywords were identified. Since authors tend to use slightly different keywords to convey similar concepts, the keywords were manually checked for similarities and then categorised according to a modified classification of Bartolini et al. (2019). The further analysis does not include 59 keywords categorised as "other". The classification below displays the 16 proposed keyword groups (with a given number of keywords in the group) alongside the author keywords and their frequencies (if the frequency is higher than one). It starts with the most numerous keyword groups:

1. **Methods (63)**: optimisation (7), constraint programming (3), modelling (3), case study (2), gradient boosting tree (2), integer programming (2), mixed integer programming (2), multi-objective optimisation (2), simulation (2).
2. **Energy (48):** renewable energy (6), energy (5), energy storage (4), liquid air energy storage (4), renewable energy source (2), solar energy (2).
3. **Energy efficiency (37):** energy efficiency (13), energy consumption (6), energy conservation (2), energy optimisation (2), energy saving (2).
4. **Sustainability (36):** sustainability (12), environmental sustainability (5), sustainable development goal (2).
5. **Storage (34):** cold storage (6), automated storage and retrieval system (5), shuttle-based storage and retrieval systems (3), storage location assignment (3), inventory(2), refrigeration (2).
6. **Green supply chain (29):** sustainable supply chain (6), cold chain (5), green supply chain (4), supply chain (4), food supply chain (2).
7. **Warehousing (28):** warehouse management (6), warehouse (5), refrigerated warehouse (2), warehouse organisation (2), warehousing (2).
8. **Carbon footprint (26):** carbon emission (5), carbon footprint (5), greenhouse gas emission (4), decarbonisation (3), life cycle assessment (2).
9. **Green logistics (22):** sustainable logistics (7), logistics (5), city logistics (2), electric vehicle (2), green logistics (2).
10. **Warehouse building design (21):** photovoltaic (3), design optimisation (2), integrated facility design (2).
11. **Green warehousing (18):** green warehousing (8), sustainable warehousing (4), green warehouse (3).
12. **Order picking (14):** order picking (3), route optimisation (2).
13. **Automated warehouse (13):** automated warehouse (3), digital twin (2).
14. **Decision-making (13):** decision-making (3), multi-criteria decision-making (2).
15. **Material handling (13):** material handling (4), material handling equipment (3).
16. **Handling equipment (9):** forklift (2), lithium-ion battery forklift (2), stacker crane (2).

The keywords in the analysed literature are highly diverse. Nearly half appear only once and have no close equivalents in other studies, highlighting the field's fragmentation. Despite this, clear thematic patterns emerge. The most significant keyword cluster reflects a strong methodological focus, frequently using terms such as *optimisation*, *modelling*, *constraint programming*, and *simulation*. This indicates a clear preference for quantitative and analytical approaches to sustainable warehouse management. The second major cluster centres on *energy* and *efficiency*, confirming energy's central role in GW research. A third major theme, *sustainability*, demonstrates the close connection between warehousing studies and broader sustainable development agendas.

Keyword co-occurrence analysis shows that 23 keywords meet the threshold of appearing at least three times; this number drops to 14 if the threshold is raised to four. The most frequently used and strongly connected keywords include *energy efficiency*, *sustainability*, *green warehousing*, *optimisation*, *sustainable logistics*, *energy consumption*, *sustainable supply chain*, *renewable energy*, *cold storage*, and *warehouse management*.

Fig. 3 visualises the co-occurrence network: each node represents a keyword, with node size reflecting total link strength. The strongest connections are *energy efficiency*, *sustainability*, *optimisation*, *green warehousing*, and *energy consumption*. The analysis identified 24 keyword clusters, ranging in size from four to 20 terms. Unconnected keywords are excluded from the figure. Overall, the findings highlight a strong research emphasis on improving energy efficiency, integrating renewable energy sources (RES), applying optimisation techniques, and reducing the carbon footprint of warehouse operations.



Note: Node size reflects the total link strength of keywords occurring more than three times.

Figure 3. Co-occurrence links and strengths among different author keywords

Source: authors' work based on www.scopus.com [10-05-2025].

Citation and Co-Citation Analysis

Citation analysis is a core component of bibliometrics. Examining citation patterns and frequencies helps measure the impact of scientific work, identify research trends, support literature searches, guide research policy, and enhance scholarly communication (Nightingale and Marshall, 2012). As part of this study, we conducted both citation and co-citation analyses.

We first set a minimum threshold of 50 citations per document to focus the analysis on the most influential and widely recognised studies in the field. Out of 95 publications, 11 met this criterion and were included in the analysis. Four of these, by Tiwari et al. (2018), Fahimnia et al. (2015), Meneghetti and Monti (2015), and Mashud et al. (2022), each received over 100 citations. A cluster of four interlinked papers authored by Ries et al. (2017), Tappia et al. (2015), and Meneghetti and Monti (2013, 2015) also emerged. Five authors met the criteria of publishing at least four documents with over 50 citations: Sara Perotti, Antonella Meneghetti, Salvatore Digiesi, Francesco Facchini, and Giorgio Mossa. This highlights the significant contribution of Italian researchers to this field.

A co-citation analysis was also performed on the references cited across the dataset. Nine of 3,384 cited references met the threshold of being cited at least three times. The total co-citation link strength was calculated to identify those with the most significant influence (see Table 2).

Table 2. Cited references with the greatest total link strength

Cited reference	Citations	Total link strength
Marchet et al. (2015)	3	4
Meneghetti and Monti (2013)	3	4
Tappia et al. (2015)	3	4
Bartolini et al. (2019)	3	2
de Koster et al. (2007)	4	2
Ene et al. (2016)	3	2
Gu et al. (2007)	5	2
Meneghetti and Monti (2015)	3	2
Hämäläinen et al. (2000)	6	0

Source: authors' work based on www.scopus.com [12-05-2025].

Conclusions

The first and only comprehensive study dedicated to a systematic literature review on GW was conducted in 2019 by M. Bartolini, E. Bottani, and E.H. Grosse. Our work extends their research to cover 2007–2024, including a bibliometric analysis and a systematic literature review on a new research sample. This sample was extracted using three keywords: *sustain**, *warehouse**, and *energy*. Unlike the earlier study, we included an energy-related keyword to highlight the role of energy efficiency in green warehouse operations.

The research revealed that these topics remain underexplored. Most publications appeared after 2015, peaking in 2024. Key disciplines include engineering, computer science, and energy. Only 34 authors have written more than one article, and just five have authored at least four. This shows how fragmented the field still is and helps identify research gaps.

There are a few contributions from the social sciences, particularly in economics and finance. Keyword analysis focuses on quantitative research, energy efficiency, sustainability, automation, and emission reduction. Optimisation and simulation are dominant methodologies, particularly constraint programming, integer/mixed-integer programming, mathematical modelling, and simulation-based case studies. Machine learning, decision-making under uncertainty, and strategic support systems are less explored. The absence of meta-analyses limits broader insights.

Warehouse process optimisation and operational efficiency are well covered. However, studies that measure the real environmental impact of warehouse technologies are scarce. Advanced solutions like cold storage and automated systems need further exploration regarding their sustainability alignment, especially in robotics, drones, and smart energy systems. Geothermal energy and smart storage also require more practice-oriented evaluations.

The technical design of warehouse structures, including photovoltaic systems and thermal insulation, is advanced. Still, new solutions integrating environmental and operational goals are needed. Research continues on autonomous, energy-efficient material handling and its potential to reduce indoor logistics emissions. While the literature discusses circular economy and green logistics, warehouse systems do not fully adopt these ideas. End-to-end life cycle thinking and sustainable design remain in early development. Further studies on transportation electrification and structured waste management are also needed. The warehouse's role in enabling closed-loop and green supply chains

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is unexamined mainly in the broader supply chain context. Full GW integration is essential for achieving long-term environmental and operational objectives.

Public policy is key to promoting sustainability in warehousing through financial and regulatory support. Technologies like geothermal energy and intelligent energy systems can be promoted via subsidies, tax relief, or preferential loans. For example, Germany's *Klimaschutzoffensive* supports renewable investments, France's *France Relance* offers tax incentives for zero-emission warehouses, and the Netherlands uses MIA/Vamil to promote green roofs and geothermal systems. These cases show how policy can accelerate the green transition. Future policies should also support smart storage, warehouse transport electrification, and systematic waste management in line with EU climate goals.

Despite progress in developing GW concepts, the shift toward energy-resilient, low-emission, and resource-efficient warehouses is still underway. Future research should explore the intersection of innovation, optimisation, energy management, and sustainability, supported by empirical evidence and interdisciplinary collaboration.

Our study has limitations that point to future directions. Further research should expand keyword selection (e.g., *material handling*, *carbon*, *emission*) and use additional databases like Web of Science or Google Scholar. Including non-peer-reviewed sources, books, and non-English literature may also help uncover overlooked contributions. Additionally, while ensuring the inclusion of highly influential works, the chosen citation threshold of 50 citations per document excluded recent but potentially impactful studies.

The contribution of the authors

Conceptualisation, A.B. and I.L.-P.; literature review, A.B. and I.L.-P.; methodology, A.B.; formal analysis, A.B. and I.L.-P.; writing, A.B. and I.L.-P.; conclusions and discussion, A.B. and I.L.-P.

The authors have read and agreed to the published version of the manuscript.

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ZIELONE MAGAZYNOWANIE I ZRÓWNOWAŻONY ROZWÓJ W KONTEKŚCIE TRANSFORMACJI ENERGETYCZNEJ: ANALIZA BIBLIOMETRYCZNA I PRZEGLĄD LITERATURY

STRESZCZENIE: Artykuł przedstawia analizę bibliometryczną i przegląd literatury dotyczący zielonego magazynowania (GW) w kontekście zrównoważonego rozwoju i transformacji energetycznej. Badanie obejmuje 95 recenzowanych publikacji z bazy Scopus (2007–2024), w celu zidentyfikowania trendów badawczych, kluczowych zagadnień oraz podejść metodologicznych. Z wykorzystaniem narzędzia VOSviewer wskazano główne klastry tematyczne, koncentrujące się wokół efektywności energetycznej, zużycia energii, optymalizacji i wykorzystania energii odnawialnej. Zainteresowanie GW znacząco wzrosło od 2015 r., szczególnie w dziedzinach inżynierii i informatyki, przy istotnym wkładzie ze strony badaczy z Włoch, Chin i Indii. Choć dominują badania ilościowe oparte na optymalizacji, integracja narzędzi wspomagania decyzji, ocen cyklu życia i metod interdyscyplinarnych pozostaje ograniczona. Brakuje również badań z obszaru nauk społecznych. Przegląd wskazuje na potrzebę prowadzenia większej liczby badań empirycznych, opartych na praktyce, dotyczących technologii magazynowych i inteligentnych systemów energetycznych w ramach modeli cyrkularnych i zielonych łańcuchów dostaw. Niniejsze opracowanie wypełnia istotną lukę, łącząc GW ze zrównoważonym rozwojem ukierunkowanym na energię, i proponuje powtarzalne ramy badawcze, które mogą wspierać przyszłe prace nad globalną zieloną transformacją.

SŁOWA KLUCZOWE: zielone magazynowanie, zrównoważony rozwój, transformacja energetyczna, analiza bibliometryczna, przegląd literatury