Ethical Statement- Not applicable

A retrospective analysis of the evolution of ergonomics for environmental sustainability (2011-2021)

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A retrospective analysis of the evolution of ergonomics for environmental sustainability (2011-2021)

Ergonomics for environmental sustainability has been rapidly gaining attention in the scientific community. So far, a large part of the literature has focused on specific dimensions of *ergonomics for environmental sustainability*, such as green designs, green buildings, environmental education, and sustainability frameworks. However, there is a necessity for an integrated study that presents the summary of published literature supported by detailed bibliometric characteristics. To address this gap, this study examined 418 articles on *ergonomics for environmental sustainability* and analysed them through bibliometric and network analysis. Major findings reveal the publication trends in *ergonomics for environmental sustainability* from 2011 to the present, the most productive and influential authors, and the most influential articles. This study also identifies the co-citation structure, bibliographical couplings and keyword co-occurrences among these articles. This study findings also provide a summary of current research and present a robust roadmap for future directions in *ergonomics for environmental sustainability*.

Practitioner summary: This paper presents a bibliometric and network analysis of the academic literature in the domain of *ergonomics for environmental sustainability*. The study provides comprehensive insights into the relevant literature and identifies global research foci and future scopes. This study can guide practitioners in identifying the specific aspects of *ergonomics for environmental sustainability* to reduce global environmental impacts.

Keywords: Ergonomics for environmental sustainability; Sustainability; Bibliometric analysis; Network analysis, Co-occurrence networks

1. Introduction

Ergonomics is the study of fitting a task to humans to improve workplace productivity, efficiency, and effectiveness (Karwowski, 2005). Initially, the domain of ergonomics included humankind's efficiency and productivity issues, but it explored sustainability issues less. Later, these issues were dealt with by a newly emerging discipline, i.e., ergonomics for environmental sustainability (Hanson, 2013). Thus, ergonomics for environmental sustainability is defined as "*ergonomics interventions that have a pro-nature focus; specifically, ergonomics that focus on human affinity with the natural world"*.

Specifically, this domain provides a better understanding of the role of human-natural environment relationships in achieving sustainability goals (Thatcher, 2014). In simple terms, "ergonomics for environmental sustainability" can be defined as applying ergonomics/human factors to the design of products, work environment, jobs, and systems to reduce the negative impact on nature. It also focuses on developing human systems that integrate fully with natural environments sustainably. These objectives can be achieved by considering the following: (1) How can humans and industrial manufacturing accelerate natural capital conservation, preservation, and restoration? (2) How can we connect humans with nature that may *facilitate human well-being and effectiveness?* Hence, an integrated view of environmental sustainability and *ergonomics* has gained significant attention and has attracted scholars in the past two decades.

1.1. Sustainable development and human factors

According to the World Commission report, *sustainable development* is defined *as the development that fulfils the needs of the current era without jeopardising the growth and ability of future generations to fulfil their own needs* (Brundlandt 1987). This sort of development has evolved as a multifaceted balancing act between the economic, social, and natural capital, also known as the *Triple Bottom Line* (TBL) approach. The TBL approach assumes that poverty often intensifies the environment's negative impact by causing over-exploitation of available resources. Therefore, the TBL approach advocates uplifting economic and social capital to diminish environmental impact.

Explicably, Steimle and Zink (2006) discussed that sustainable development and human factors need to focus on human elements within the larger system (i.e. social capital). In this regard, Docherty et al. (2002) highlighted the relationship between sustainable development and human factors by building sustainable work systems. Sustainable work systems integrate work that

satisfies the physical, physiological, and psychological parameters of human functioning. Steimle and Zink (2006) inspired ergonomists to contribute to this domain by developing sustainable products, designing efficient work, and ensuring safe operation that might eventually reduce environmental impacts. Hanson (2010) suggested the idea of integrating "ergonomics" and "environmental sustainability" to focus on how ergonomics can contribute to protecting and securing our environmental impact. Therefore, incorporating the goals of "ergonomics" such as effectiveness, efficiency, health and safety, and usability with "environmental sustainability" such as conservation, preservation, and recycling to achieve pragmatic organisational strategies and competitive advantage has gained increased attention (Thatcher, 2013). This interrelationship is shown in Figure 1.

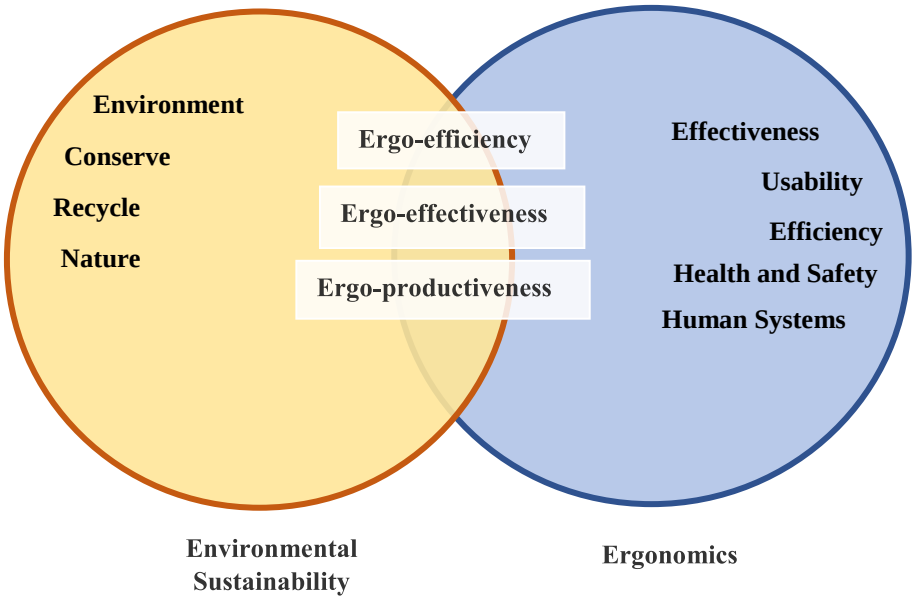

Figure 1 Caption: The interrelationship between *Environmental sustainability* and *ergonomics* practices (Based on Thatcher, 2013)

Figure 1 Alt Text: Two different-coloured circles represent environmental sustainability and ergonomic practices. "**Environmental Sustainability" set represents** (Orange) - Environment; Conserve; Recycle; Nature. "**Ergonomics" set represents** (Blue) - Effectiveness; Usability; Efficiency; Health and Safety; Human Systems, **Intersection represents** - Ergo-efficiency; Ergo-effectiveness; Eco-productivity

However, only a few scholarly studies in *ergonomics for environmental sustainability* have comprehensively included the significant aspects of this nascent domain (Martin et al., 2013;

Thatcher, 2013; Hanson, 2013). While some scholarly works offered useful insights through a structured consolidation of ergonomics for environmental sustainability, they were often limited to particular themes and topical issues such as *design* (Thatcher, 2013; Hedge, 2013), *design of green buildings* (Thatcher et al., 2014; Hedge, 2013), and *mental models* (Kalantzis et al., 2016). Besides, most of these studies were inclined to employ a conventional literature review technique (for instance, a synthesis or meta-analysis). Upon investigation, it was found that state-of-the-art of extant literature based on bibliometric characteristics of erstwhile-published articles has not been reported or examined before. The only study that comes close to ours' is by Bolis et al. (2022), who reviewed the contribution of ergonomics and human factors to sustainable development. Our study also offers novel observations on the entire discipline of *ergonomics for environmental sustainability*. To fulfil this aim, our study presents a comprehensive bibliometric analysis by integrating environmental sustainability and ergonomics and examines its subsequent impacts on sustainability. Therefore, this study uses a combination of bibliometric and network analyses to answer the following research questions:

RQ1: *How has the research landscape of ergonomics for environmental sustainability developed over time?*

RQ2: *Which/who are the most influential journals, articles, academic institutions, affiliated authors, and academic connections within the area of ergonomics for environmental sustainability?*

RQ3: *What are the dominant research areas in ergonomics for environmental sustainability?*

RQ4: *What are the avenues for future research in ergonomics for environmental sustainability?*

Currently, scholars are frequently applying bibliometric and network analyses due to their capability of detailed literature analysis with the help of dedicated software (Bolis et al., 2022; Bornmann and Mutz, 2015; Fahimnia et al., 2015; Albort-Morant et al., 2016; Vallaster et al., 2018; Dzikowski, 2018). These techniques allow scholars to (i) explore the contemporary research themes based on published literature in a particular domain; (ii) analyse published works and identify the trends and patterns; (iii) provide potential future research directions; (iv) categorise the published studies in clusters of connected scholars; (v) identify the associations among the journals, researchers, and keywords.

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This study advances the discipline of *ergonomics for environmental sustainability* in multiple ways. First, using a bibliometric analysis of academic articles published in the last ten years, it identifies the evolution of *ergonomics for environmental sustainability* since inception. Second, this study evaluates the progress in current research and trends of scholarly contributions in ergonomics for environmental sustainability. Second, it categorises the published literature based on widely acknowledged characteristics and rankings, such as top productive authors, top-cited authors, top journals, most-used keywords, top productive countries, and the top productive research institutions. Third, the study conducts an extensive network analysis of co-cited papers, bibliographically-coupled authors, and keyword co-occurrences across the domain of *ergonomics for environmental sustainability*. Using this data-driven approach, scholars can dig deeper into *ergonomics for environmental sustainability* instead of restricting themselves to a pre-designed set of potential topics during a systematic literature review. Fourth, this study further examines the results and proposes potential research directions for future studies.

The rest of the paper is organised as follows. Section 2 explains the research methodology adopted in this study. In Section 3, the bibliometric and network analyses are conducted. Section 4 discusses the results, reports the significant findings and implications, and proposes future research directions. Finally, the study concludes in Section 5.

2. Research methodology

This analysis aims to represent and evaluate the present status of literature to identify the leading trends of *ergonomics for environmental sustainability* in terms of research impact, research topics, institutional affiliations, and countries to provide insights for possible future research directions (Tranfield et al., 2003). This study employed PRISMA methodology, along with bibliometric and network analysis. The methodology in this study was commensurate with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) checklist, followed by systematic literature reviews and meta-analyses (Liberati et al., 2009). This systematic analysis of *ergonomics for environmental sustainability* helps to identify the most important topics/themes and less explored areas of research and present the perceptiveness of current research interests and possible future directions, in line with the PRISMA methodology.

2.1. Identify the database, keywords, and time horizon of the bibliometric study

We chose published articles for our bibliometric analysis from the academic repository *Scopus*, a globally 7ecognized database. We included the research articles published between 2011 and 2021 because the discipline of *ergonomics for environmental sustainability* is relatively nascent and emerged fully after 2010.

In this study, we allowed the following keywords for bibliometric analysis: "ergonomics", "human factors", "green", and "environmental". By adopting the PRISMA methodology, we combined these keywords by using "AND" and "OR" operations, as shown in Table 1. We have carefully checked all the keyword combinations and comprehensively covered all possible aspects specified.

Table 1. Search results after filtering and refinement of articles in *ergonomics for environmental sustainability* (2011-2021)

Search string	**Number of papers**
KEY (ergonomics OR human factors) AND KEY (green OR environmental)	**448**
The search results after filtration and refinement (excluding duplicate instances, non-English articles, and articles without author details in Scopus)	
Total articles after refinement	**418**

2.2. Inclusion and Exclusion criteria

We adopted a two-step approach for extracting the research articles in this bibliometric analysis. In the first step, we conducted an initial search between August and September 2021 to extract articles published between 2011 and 2021. The results from our analysis were saved in a CSV file to extract tags such as *author*, *title*, *abstract*, *institutional affiliation*, and *research country*. This study used a systematic approach to collect accurate bibliometric data, as shown in Figure 2. We identified 448 articles based on the initial search term criteria. Then, we manually read each article's abstract to ensure its relevance of inclusion. Industry white papers, working papers, duplicate papers, articles written in a non-English language and articles related to the medical field were discarded to make the study consistent. In this manner, each selected article was carefully analysed to include only those articles that connect *environmental sustainability* and *ergonomics*. Based on these inclusion and exclusion criteria, 418 research articles were found to be unique and relevant, and 30 were rejected. Table 2 provides the descriptive information about these selected articles. 1421 authors produced these 418 research articles in the area of *ergonomics for*

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environmental sustainability. Out of these 418 research articles, 31 were single-authored publications. The collaboration index for authors who worked on *ergonomics for environmental sustainability* was calculated as 3.59.

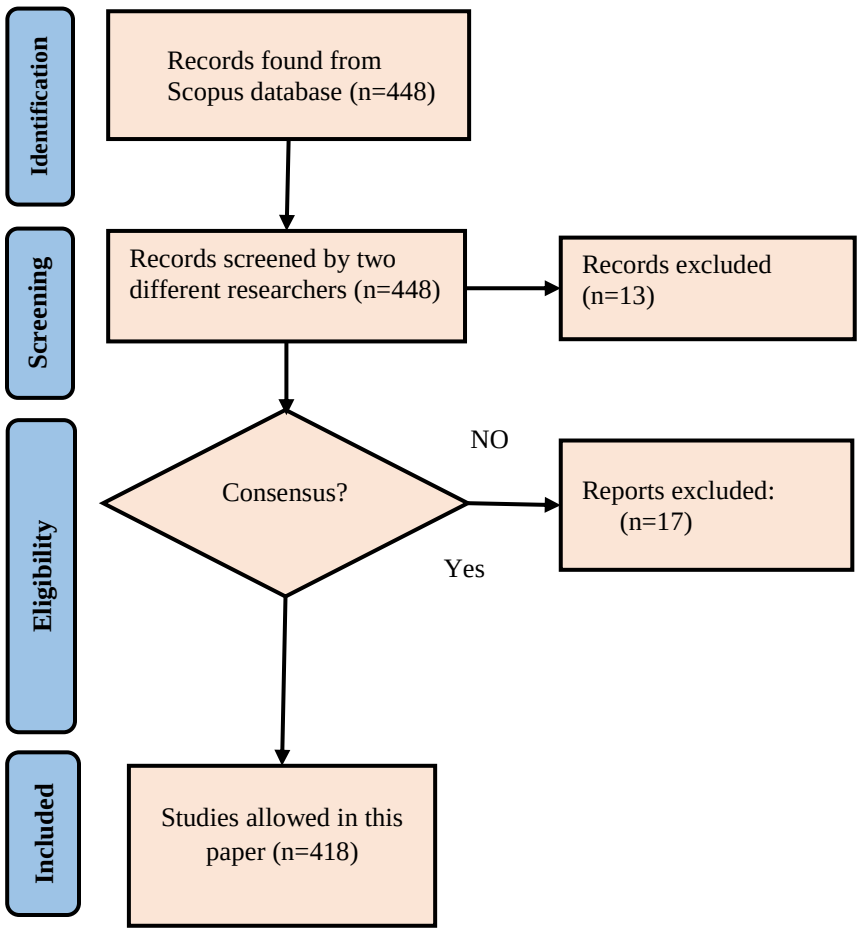

Figure 2 Caption: Data collection process as recommended by PRISMA (2020)

Figure 2 Alt Text: Flow diagram for the data collection process, represented by process box and decision box

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Table 2. Overall information about the bibliometric collection of articles published in *ergonomics for environmental sustainability*	
Description	**Results**
Main Information about Bibliometric Data	
Period	2011 - 2021
Sources (Journals, Books, etc.)	196
Documents	418
Average years from publication	4.91
Average citations per document	15.72
Average citations per year per doc	2.316
References	18677
Author Information	
Author's Keywords (DE)	1491
Authors	1421
Author Appearances	1549
Authors of single-authored documents	31
Author Collaboration	
Single-authored documents	31
Documents per Author	0.294
Authors per Document	3.4
Coauthors per Documents	3.71
Collaboration Index	3.59

3. Bibliometric analysis

Bibliometric analysis is a method to systematically review and extract scholarly articles based on keywords, authors, paper titles, and affiliations to identify the current research gaps for a specific domain, both geographically and content-wise (Jacobs, 2010). Bibliometric analysis helps determine the performance and research trends across countries, authors, and affiliated institutions. According to Wang et al. (2014), bibliometric findings can easily uncover the latest research directions and prominent themes in a specific research area. The results from bibliometric analyses can also guide policymakers and funding agencies while allocating research funds (Ugolini et al., 2015).

In many previous research articles, scholars have employed a variety of software packages and tools for bibliometric analysis with varying capabilities. In this study, we applied the

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bibliometrix software package in R because of its powerful graphical and statistical computational capabilities (Bretas and Alon, 2021; Dervis, 2019; Gagolewski, 2011; Liu et al., 2005; Li and Yan, 2018). Figure 3 presents the three-stage methodology of bibliometric analysis applied in our study using the R *bibliometrix* package.

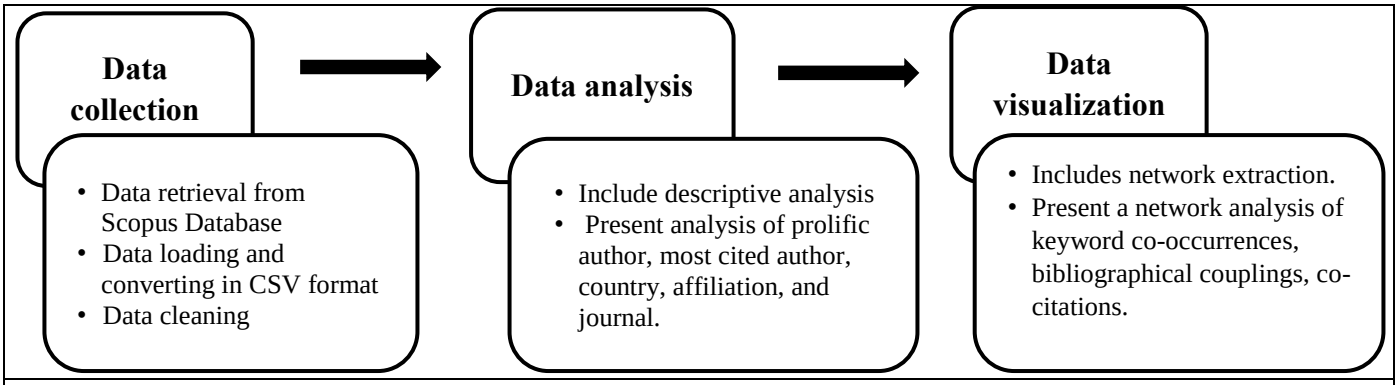

Figure 3 Caption: Three-stage methodology for bibliometric analysis of published articles in *ergonomics for environmental sustainability*.

Figure 3 Alt Text: Flow diagram for bibliometric analysis, presented in three stages with rectangle boxes. Stage 1: Data collection; Stage 2: Data analysis; Stage 3: Data visualisation

3.1. Descriptive analysis

3.1.1 Publication trend and growth of articles in Ergonomics for environmental sustainability

Since its inception, *ergonomics for environmental sustainability* has gained rapid interest among scholars. A total of 418 articles were published between 2011 to 2021 at an average annual growth rate of 4.9%. Figure 4 shows that the trend of publications in *ergonomics for environmental sustainability* has steadily increased since 2013. In 2012, twenty-eight articles were published on *ergonomics for environmental sustainability*. Until 2017, the publication of academic articles on *ergonomics for environmental sustainability* remained stagnant. However, we observed a growing number of articles (equal to forty papers per year or more) from 2018 onwards. After that, the publication of academic articles exponentially increased until it reached the highest number of 51 articles in 2021.

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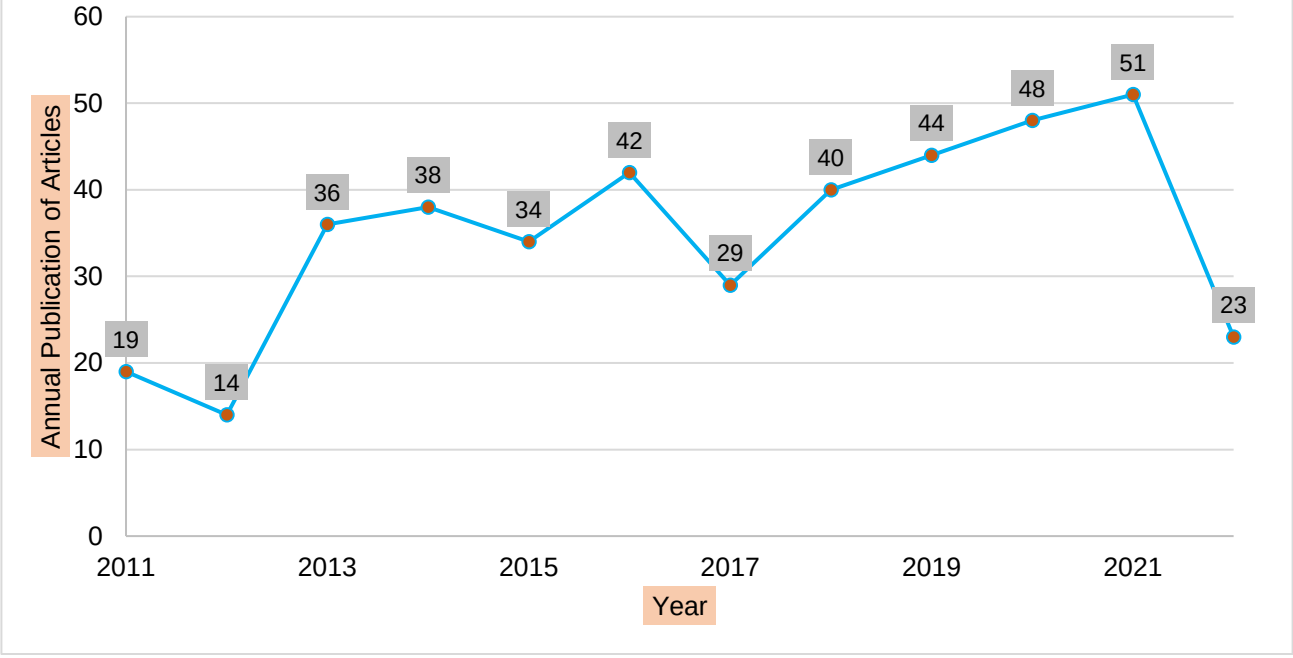

Figure 4: The annual publication of articles in the area of *ergonomics for environmental sustainability* (2011-2021)

Figure 4 Alt Text: Line chart showing the annual publications distributed in one year.

These statistics reveal that research interest in *ergonomics for environmental sustainability* has increased significantly in recent years. It re-affirms the need for a systematic summarisation of the literature, analyse them, and encapsulate the significant findings in this domain. Therefore, our study attempts to fill this gap and thus answer the first research question **(RQ1):** *How has the research landscape of ergonomics for environmental sustainability grown over time?*

3.1.2. Influential authors, most productive authors and their collaboration networks

Many researchers have contributed significantly to the growth and evolution of *ergonomics for environmental sustainability*. This study uncovered 1421 different authors who published those 418 research articles. Table 3 presents the most productive authors based on the number of articles that have substantially moulded the scholarly discussions on *ergonomics for environmental sustainability*. It is important to note that these researchers have discussed several themes, and some of them are *green buildings*, *sustainable ergonomics*, *design principles*, and *design solutions*. Then, we computed the ranking of the most productive authors in *ergonomics for environmental sustainability* based on the total citations received. Analysis revealed that *Thatcher, A* (Andrew

Thatcher) is most productive with 9 articles and 240 citations, while *Stanton, N. A* (Neville A Stanton) is the most influential author, with 313 citations.

Andrew Thatcher ranks among the most prolific authors in *ergonomics for environmental sustainability*. His published works have helped to develop the scope of the entire discipline of *ergonomics for environmental sustainability* from an academic and industrial organisation perspective. Thatcher's published articles have also examined *ergonomics for environmental sustainability* from different theoretical paradigms (Lange-Morales et al., 2014; Thatcher et al., 2018b). Moreover, his research work related to *ergonomics for environmental sustainability* has included factors such as *occupational health and safety* (Thatcher and Milner, 2014a), *organisational design*, *workplace safety*, *workplace layout*, and also emphasised the role of *sustainable behaviour* and *green building designs* (Thatcher and Milner, 2014b).

Next, we examined the collaboration network of the authors who have published in the domain of *ergonomics for environmental sustainability* (see Figure 5). The size of each node is proportional to the number of published articles, and the connecting link between two authors denotes their mutual collaboration. Five author-based clusters are visible in the collaboration network, which we represent with different colours. Some of the significant authors among these clusters are Thatcher. A; Sgarbossa. F; and Sznelwar. L. I., who represents the big-sized nodes on the network. These results are also comparable to the publication details in *ergonomics for environmental sustainability*, already presented in Table 3.

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Table 3 - Top 5 most productive and influential authors with the number of published papers and total citations in *ergonomics for environmental sustainability* (2011-2021)

Rank	Authors	Discipline / context	Theme of studies	Affiliation	Country	NP	TC	AC	h
1	Thatcher, A	Sustainability, Ecological, Ergonomics for environmental sustainability, Psychology	Cognitive search strategies, the definition of ergonomics for environmental sustainability, System approach, Supply chain ergonomics, Green building, Macro ergonomics, Sustainable technologies, Ecological ergonomics	University of the Witwatersrand	South Africa	9	240	26.67	7
2	Stanton, N. A	Safety, accident, human factor, Product design	Sustainable design	University of Southampton	United Kingdom	7	313	44.71	7
3	Peruzzini, M	Human factors, Virtual reality	Design for a sustainable product, social sustainability	University of Modena and Reggio Emilia	Italy	6	35	5.83	4
3	Salmon, P.M	System thinking, ergonomics	Sociotechnical system	University of the Sunshine Coast	Australia	6	168	28	6
4	Battini, D	Ergonomics, Waste Management	Sustainable waste management	University of Padova	Italy	5	205	41	4
5	Bolis, I	Sustainable development, Corporate social responsibility, Physical ergonomics, Health, and safety	Sustainable organisation, sustainability in occupational health, Sustainable entrepreneurship	Universidade de São Paulo	Brazil	5	60	12	3
5	Sznelwar, L I	Workplace safety, sustainability	Building sustainable organisation, Performance measurement, work analysis	University of Sao Paulo	Brazil	5	60	12	3

*NP= Number of papers; TC= total citation; AC = Average citation per paper, h = h-index.
Note: Ranking based on total papers in Scopus; Analysis conducted on 14th September 2021

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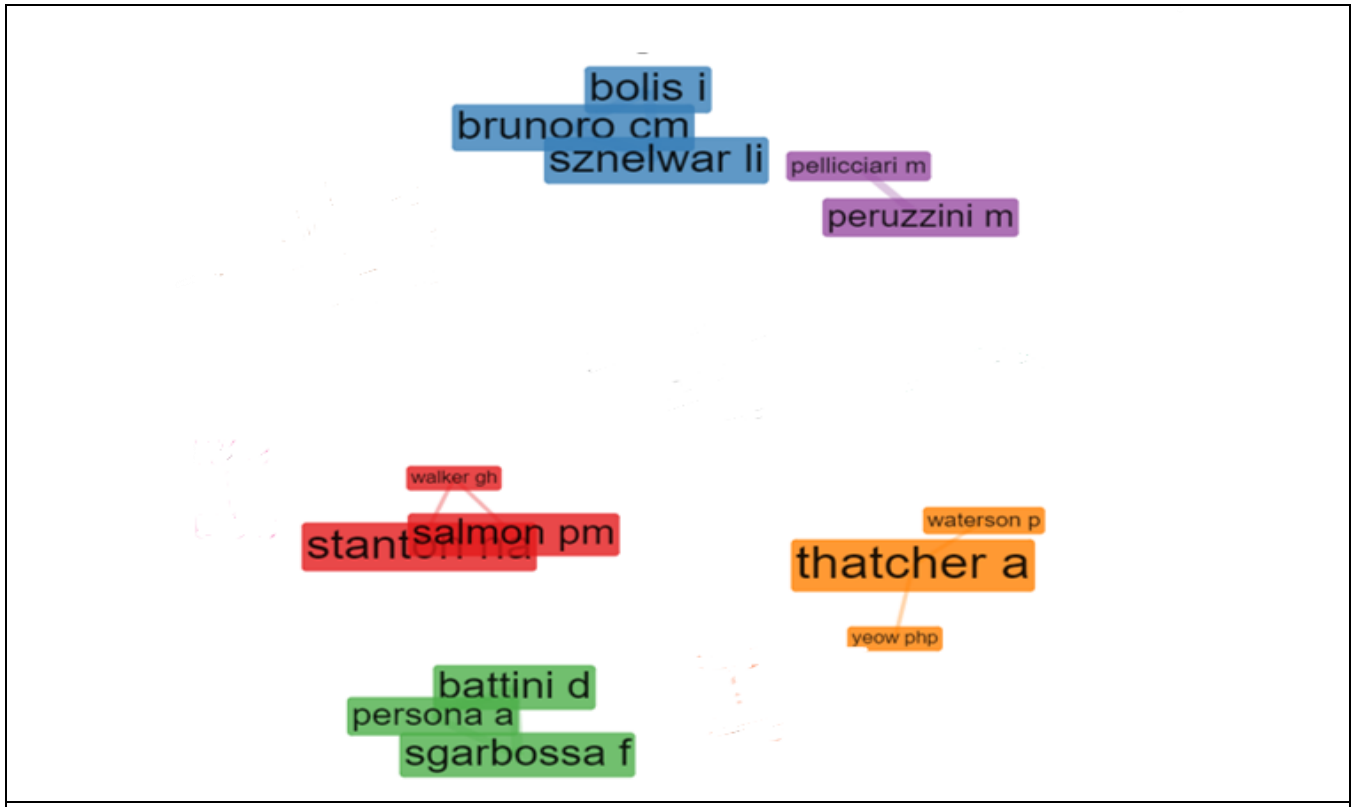

Figure 5 Caption: Author Collaboration cluster in *ergonomics for environmental sustainability* (2011-2021).

Figure 5 Alt Text: Author collaboration network, mentioned in three different clusters with different colours. Some of the significant authors of these clusters are Thatcher. A (Yellow cluster); Sgarbossa. F (Green cluster); Sznelwar. L. I (Blue cluster).

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3.1.3. Major journals publishing articles in ergonomics for environmental sustainability

Next, we present the relevant journals which regularly publish scholarly articles in the emerging area of *ergonomics for environmental sustainability*. The analysis reveals that 29 relevant journals contributed to publishing those 418 articles. Further, among these 29 relevant journals, the top 10 contributed 239 articles, constituting approximately 41.4% of the total. Figure 6 presents the top 10 journals in *ergonomics for environmental sustainability*. Among these relevant journals, the top three are (i) *Applied Ergonomics* (71 articles), followed by (ii) *Ergonomics* (53 articles) and (iii) *International Journal of Industrial Ergonomics* (24 articles).

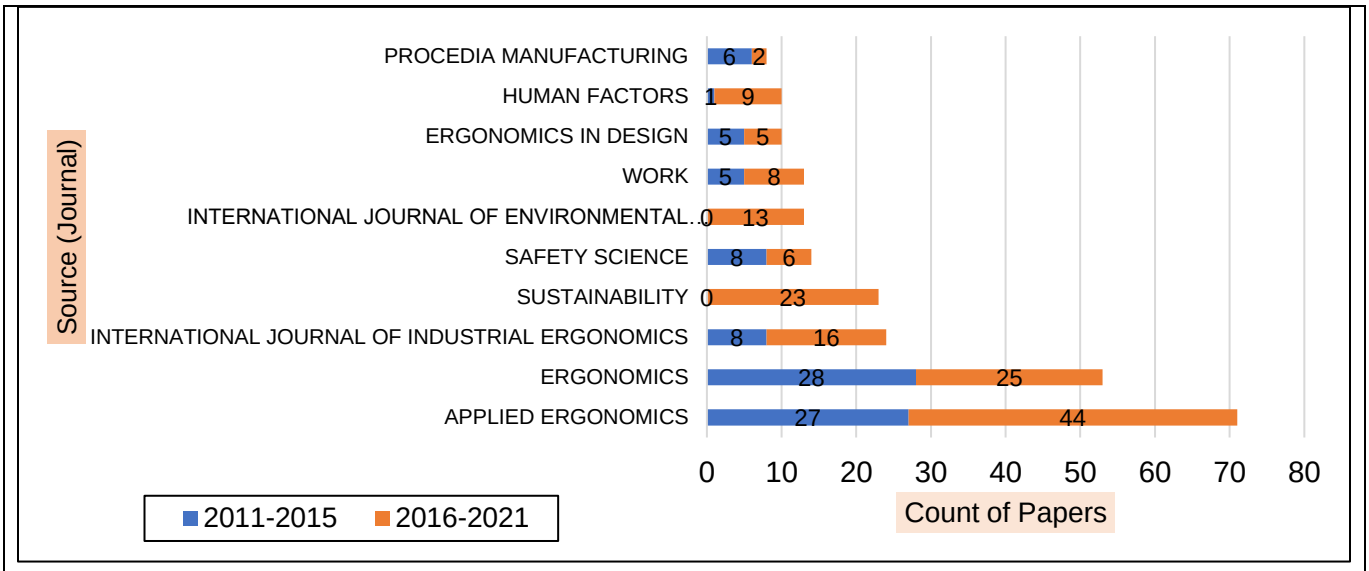

Figure 6 Caption: Top 10 sources publishing on *ergonomics for environmental sustainability* (2011-2021)

Figure 6 Alt Text: Bar chart showing the year-wise highest paper publishing journal in the area of ergonomics for environmental sustainability, with the paper count, from 2011 until 2021.

3.1.4. Country-wise analysis of articles published in ergonomics for environmental sustainability

From our bibliometric analysis, the top 10 countries based on the total number of publications in *ergonomics for environmental sustainability* from 2011 to 2021 are shown in Figure 7. Among those countries, USA is at the top rank with 51 research articles, followed by Italy, UK, and Brazil. The ranking was performed based on the total number of publications using R software (*bibliometrix* package). Further, the overall geographical distribution reveals that research and industry practices on *ergonomics for environmental sustainability* have attracted organisations and research centres worldwide, as shown in Figure 8.

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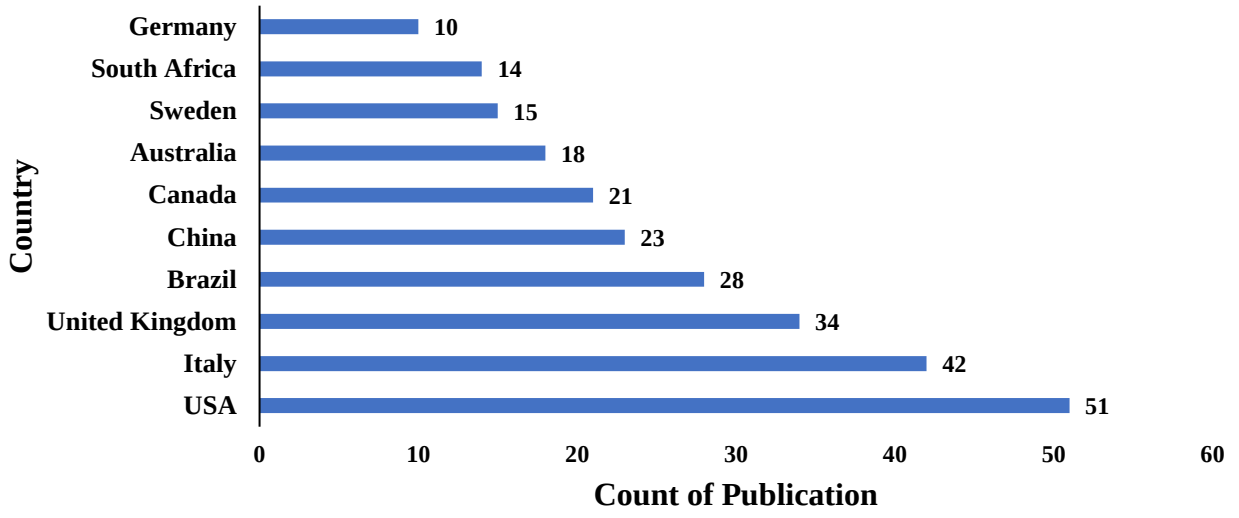

Figure 7: Top 10 countries with papers counts in *ergonomics for environmental sustainability* (2011-2021)

Figure 7 Alt Text: Bar chart showing the top ten countries with the paper count. 1. USA-51; 2. Italy-42; 3. United Kingdom-34; 4. Brazil-28; 5. China-23; 6. Canada-21; 7. Australia-18; 8. Sweden-15; 9. South Africa-14; 10. Germany -10

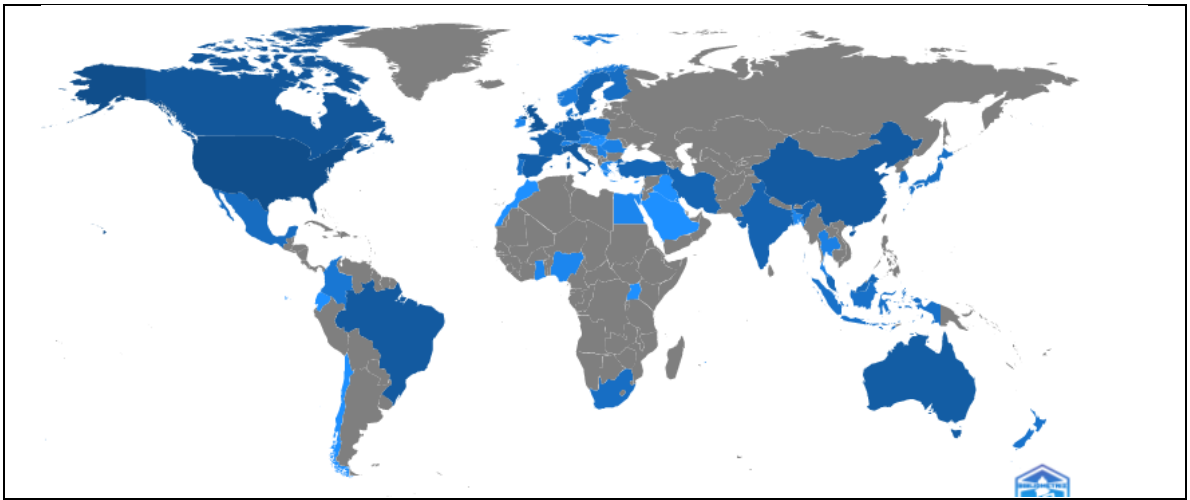

Figure 8 Caption: Geographical distribution of count of publications in *ergonomics for environmental sustainability* (2011-2021).

Figure 8 Alt Text: Twelve countries highlighted in blue on the world map represent the most active countries that published articles in the domain of *ergonomics for environmental sustainability* from 2011 until 2021.

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Next, we analysed the collaborative networks within the domain of *ergonomics for environmental sustainability* that spread across various countries. In this network, we listed authors from affiliated countries who had published at least 15 research articles on *ergonomics for environmental sustainability*. Affiliated countries in the network that were not connected were dropped and taken for further analysis. The top 22 countries that collaborated in *ergonomics for environmental sustainability* are presented in Figure 9. The node's size indicates the number of publications, and the link's thickness reflects each country's collaborative strength. Each colour indicates a collaboration cluster, with the following countries leading within each cluster - 1. *USA (Red cluster); 2. Italy (Green cluster); and 3. Spain (Brown cluster).*

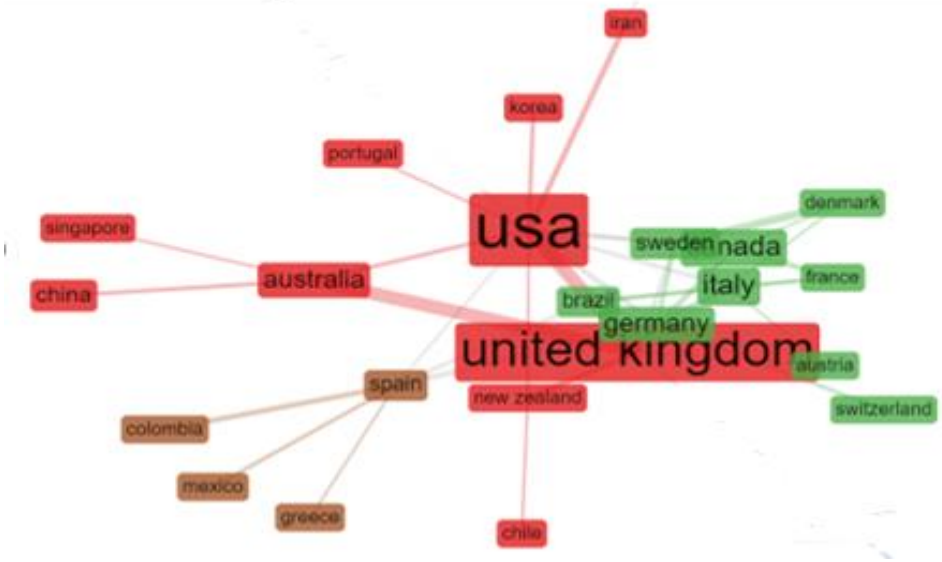

Figure 9. The top collaborative networks between countries in *ergonomics for environmental sustainability* (2011-2021)

Figure 9 Alt Text: Three clusters represent the collaborative networks between countries in *ergonomics for environmental sustainability*, denoted by different colours. Following countries lead within each cluster - 1. USA (Red cluster); 2. Italy (Green cluster); and 3. Spain (Brown cluster)

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3.1.5. Affiliation analysis of academic institutes

Next, we identify the top-performing institute(s) in developing the domain of *ergonomics for environmental sustainability*. We present the top 10 institutes whose scholars had published highly (see Figure 10). Among those top contributing institutes, the University of the Witwatersrand in South Africa ranks first with 14 articles, and the most productive author is *Andrew Thatcher*. Next, the Universiti Teknologi Mara, Malaysia, secured the second position with 10 papers.

Figure 11 presented the collaborative network among the Institutions in ergonomics for environmental sustainability and revealed that many institutions have strong international collaboration relationships following the coauthored publications. The University of the Witwatersrand worked closely with Monash University Malaysia and Loughborough University, as shown in the red cluster in Figure 11. Similarly, both the University of Southampton and Monash University (Blue cluster) actively worked. Therefore, the findings reported in sub-sections 4.1.2 until 4.1.5 answer our second research question (***RQ2):*** *Which are the most influential journals, articles, academic institutions, affiliated authors, and academic connections within the area of ergonomics for environmental sustainability?*

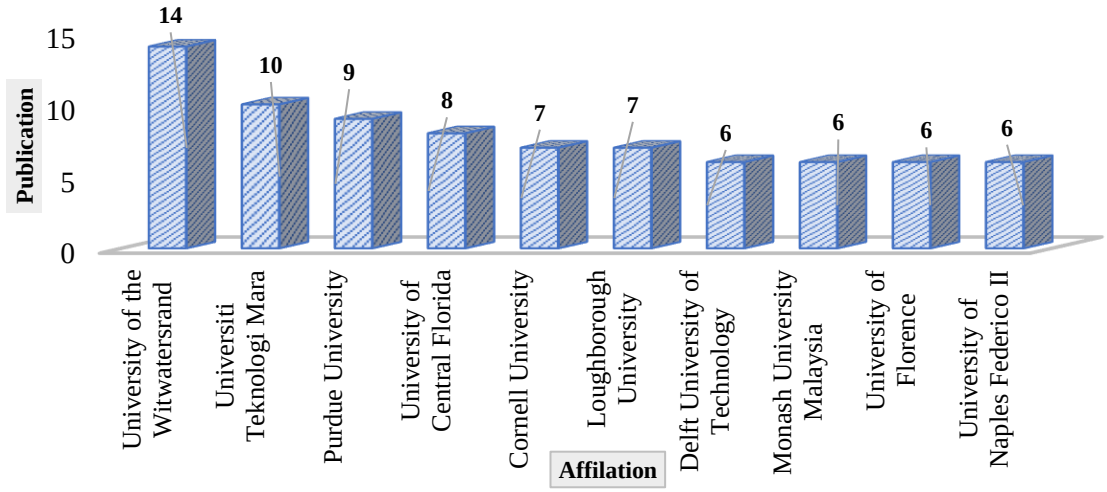

Figure 10 Caption: Top 10 highest contributing institutions in *ergonomics for environmental sustainability* (2011-2021).

Figure 10 Alt Text: Bar chart showing the top ten highest contributing institutions in *ergonomics for environmental sustainability* (2011-2021). 1. The University of the Witwatersrand; 2. University Technology Mara; 3. Purdue University; 4. University of Central Florida; 5. Cornell University; 6. Loughborough University; 7. Delft University of Technology; 8. Monash University Malaysia; 9. University of Florence; 10. University of Naples Federico

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Figure 11. The top collaborative network between institutions in *ergonomics for environmental sustainability* (2011-2021)

Figure 11 Alt Text: Four clusters showing the top collaborative network between Institutions in *ergonomics for environmental sustainability* (2011-2021), represented by different colours. The University of the Witwatersrand worked closely with Monash University Malaysia and Loughborough University (Red). Similarly, Cornell University and Ithaca College both worked together (Blue).

3.1.6. Keyword analysis in ergonomics for environmental sustainability

This analysis aims to identify the most frequently used words in author keywords and titles of the articles. To develop the word cloud, the following keywords: “ergonomics”, “human factors”, “environment”, and “green” were removed from the analysis because these keywords were used for the initial search and extraction of the articles. A few keywords that were synonyms were also removed to avoid repetitive word plots. Then, the top 50 keywords used in the 418 papers are shown in the word cloud in Figure 12. The top 10 author keywords are shown in Figure 13, along with their respective frequencies. The examination was performed with a collection of 1297 keywords from paper titles and author keywords that were extracted from 418 publications. The top 10 keywords (from paper titles) are shown in Figure 14. When we compare the findings from Figure 13 and Figure. 14, it reveals that, in most cases, the author-keywords are similar to the titles-keywords across the 418 publications.

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Figure 12 Caption: Word cloud of top 50 author keywords used in *ergonomics for environmental sustainability* (2011-2021).

Figure 12 Alt Text: Word cloud is a visual representation of text data with different colours. The font size of every keyword depends upon its frequency. For instance, ergonomics appears largest in the word cloud due to its highest usage in the published article in ergonomics for environmental sustainability, followed by sustainable development and ergonomics for environmental sustainability.

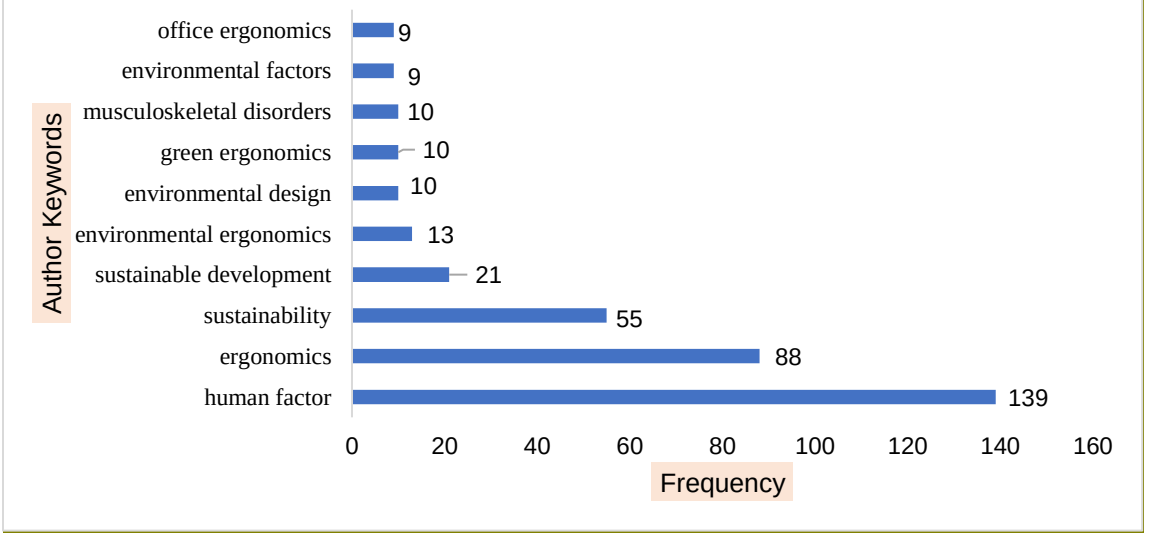

Figure 13. – Top 10 author-keywords commonly used in *ergonomics for environmental sustainability* (2011-2021)

Figure 13 Alt Text: 1. Human factor-139; 2. Ergonomics-88; 3. Sustainability-55; 4. Sustainable development- 21; 5. Environmental ergonomics-13; 6. Environmental design-10; 7. Ergonomics for environmental sustainability-10; 8. Musculoskeletal disorder-10; 9. Environmental factors-9 and 10. Office ergonomics-9.

Ethical Statement- Not applicable

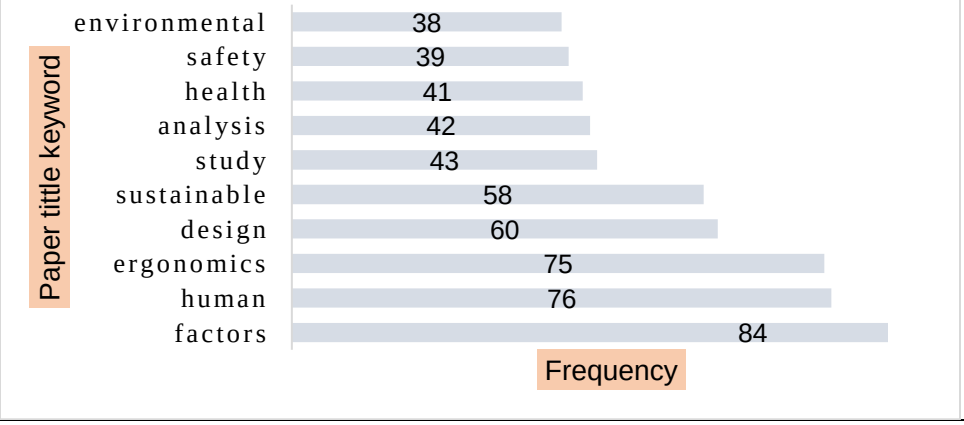

Figure 14. – Top 10 keywords used in paper titles for *ergonomics for environmental sustainability* (2011-2021)

Figure 14 Alt Text: 1. Factors- 84; 2. Human-76; 3. Ergonomics-75; 4. Design-60; 5. Sustainable- 58; 6. Study- 43; 7. Analysis-42; 8. Health-41; 9. Safety-39; 10. Enviornmental-38

3.1.7. Citation analysis in ergonomics for environmental sustainability

Citation analysis reports the number of times other publications have cited a particular publication in *ergonomics for environmental sustainability*. The average citation is 12.51 per publication in this domain (see Table 2). The top 10 papers based on the number of local citations are listed in Table 4. The number of times other articles have cited a paper (within this 418-paper network) is defined as its "local citation." The overall Scopus citations received from other articles (irrespective of this 418-paper network) for a paper is defined as its "global citation." From Table 4, we observe a significant difference between local and global citations count. It also reveals that researchers in other disciplines have not keenly noticed this domain, so it is still in its infancy. This finding is also supported by the fact that these highly cited publications have been published within the last 6-7 years.

Ethical Statement- Not applicable

Table 4. The top 10 papers in *Ergonomics for environmental sustainability* (2011-2021) based on citation measures

#	Paper Title / Author(s) / Journal	LC	GC	R (%)	NLC	NGC
1	Thatcher, A. (2013). Ergonomics for environmental sustainability: definition and scope. *Ergonomics*, *56*(3), 389-398.	20	82	24.39	11.26	4.53
2	Zink, K. J. (2014). Designing sustainable work systems: The need for a systems approach. *Applied Ergonomics*, *45*(1), 126-132.	16	88	18.18	15.67	3.91
3	Hanson, M. A. (2013). Ergonomics for environmental sustainability: challenges and opportunities. *Ergonomics*, *56*(3), 399-408.	15	44	34.09	8.45	2.43
4	Dekker, S. W., Hancock, P. A., and Wilkin, P. (2013). Ergonomics and sustainability: towards an embrace of complexity and emergence. *Ergonomics*, *56*(3), 357-364.	13	49	26.53	7.32	2.71
5	Lange-Morales, K., Thatcher, A., and García-Acosta, G. (2014). Towards a sustainable world through human factors and ergonomics: it is all about values. *Ergonomics*, *57*(11), 1603-1615.	12	31	38.71	11.76	1.38
6	Zink, K. J., & Fischer, K. (2013). Do we need sustainability as a new approach in human factors and ergonomics? *Ergonomics*, *56*(3), 348-356.	12	41	29.27	6.76	2.26
7	Thatcher, A., and Yeow, P. H. (2016). Human factors for a sustainable future. *Applied Ergonomics*, *57*, 1-7	9	26	34.62	10.76	2.00
8	Radjiyev, A., Qiu, H., Xiong, S., & Nam, K. (2015). Ergonomics and sustainable development in the past two decades (1992–2011): Research trends and how ergonomics can contribute to sustainable development. *Applied Ergonomics*, *46*, 67-75.	9	44	20.45	17.04	2.19
9	Bolis, I., Brunoro, C. M., and Sznelwar, L. I. (2014). Mapping the relationships between work and sustainability and the opportunities for ergonomic action. *Applied Ergonomics*, *45*(4), 1225-1239.	9	35	25.71	8.82	1.56
10	Thatcher, A., and Yeow, P. H. (2016). A sustainable system of systems approach: a new HFE paradigm. *Ergonomics*, *59(2)*, 167-178	7	40	17.50	8.37	3.08

LC=Local Citations; GC=Global Citations; R = ratio of LC / GC; NLC= Normalized local citation; NGC=Normalized global citation;
Note: Ranking based on total papers in Scopus; Analysis conducted on 14th September 2021

Ethical Statement- Not applicable

3.2 Networks Analysis

3.2.1. Co-citation network analysis of most influential research articles in ergonomics for environmental sustainability

Co-citation occurs when two published articles are cited in a third research article concurrently; such that the two published articles that were cited can now be deemed *co-cited* (Singh et al., 2022; Small, 1999). Their mutual association improves as more research articles start to cite them jointly (Singh et al., 2022; Small, 1999). Gupta et al. (2021) mentioned that a co-citation network presents a comprehensive analysis of the periodic progression of a given scholarly domain. The network of most cited research articles is presented in Figure 15, including spatial locations for most of the cited research articles. While generating the network, we allowed up to the top 100 co-cited authors, and isolated nodes were deleted for better network clarity.

In a co-citation network, the node size represents the total count of the citations received, while the strength of a mutual relationship depends on the closeness between two nodes. Thus, the nodes nearer to each other represent research articles that are co-cited many times. In this study, the co-citation network is comprised of different clusters, and each cluster is marked with a distinct colour (see Figure 15), denoting a specific research theme in the domain of *ergonomics for environmental sustainability*.

In Figure 15, the red cluster (Cluster 1, on the left side of the network) is the largest cluster within the entire co-citation network and comprises nine published papers. The overarching theme of this cluster is sustainability as a new approach to human factors that influences *ergonomics for environmental sustainability*. Articles belonging to this cluster are dedicated to the origin of the concept of *ergonomics for environmental sustainability* (Moray, 1993, 1995; Zink, 2013), and it is further connected with another cluster. Few research articles in this cluster have also mentioned climatic changes and other issues related to ergonomics (Hanson, 2013). This cluster also presents review articles that explore these challenges and opportunities (Thatcher, 2013; Hanson, 2013) and evolve towards a sustainable world through human factors and ergonomics (Lange-Morales et al., 2014).

The BLUE cluster (Cluster 2 on the right side of the network) includes six papers. Cluster 2 consists of the themes that address the challenges while transferring sustainable development to organisational and work systems (Hanson, 2010). This cluster also identifies the scope of ergonomics from organisational strategies (Dul and Neumann, 2009). Finally, this cluster

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effectively addresses other relevant issues such as consumption and production, transportation, and waste recycling.

Figure 15. Co-citation network of top 50 influential papers (represented by "primary author") in *ergonomics for environmental sustainability* (2011-2021)

Figure 15 Alt Text: Red cluster (Cluster 1, at the left side of the network)- Largest cluster within the entire co-citation network consists of nine published papers
BLUE cluster (Cluster 2, at the right side of the network) - comprised of six published papers

3.2.2. Bibliographical coupling network (author based) in ergonomics for environmental sustainability

Bibliographical coupling occurs when two articles cite the third paper concurrently, so the former two articles can be deemed bibliographically coupled via the third paper (Kessler, 1963). A bibliographic coupling network provides a systematic way to analyse recent trends and patterns in an author's knowledge network over time (Most et al., 2018). This study used the R bibliometrix package to construct the bibliographical-coupling network for the top 100 most productive authors. For creating this bibliographical coupling, the full-counting method was applied. A network of two clusters was generated and is shown in Figure 16. The top 100 bibliographically coupled coauthors were allowed to develop this network, while isolated nodes were deleted for more clarity.

The size of each node indicates the strength of a productive author's connections inside the cluster. This finding also suggests that those groups of references generate the highest cohesion inside the cluster. The co-citation network presents two primary clusters and is represented by two

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different colours as follows- Cluster 1: Red-colored cluster is the largest (comprised of twenty-three authors) and is located on the left side of the network. Cluster 2: Green-coloured cluster (comprised of eight authors) is located on the right side of the network.

Cluster 1 (Red colour) is the largest cluster with 23 authors; significant ones are *John R. Wilson, Andrew Thatcher, and K.J. Zink*. The research articles included in this cluster are surrounded by Andrew Thatcher and K.J. Zink's scholarly works and are located in the lower part of the network (see Figure 16). Also, the overarching theme of the articles in this cluster focuses on global environmental issues from a systems approach and emphasises global and sustainability issues with ergonomics. This cluster is relatively new and emerging.

Cluster 2 (Green colour) is the smallest and is located on the right side of the network (Figure 16). It includes eight authors; significant are *Jens Rasmussen, P.M. Salmon and N.A. Stanton*. This cluster is small, connected with Cluster 1 and focuses on ergonomic frameworks and other empirical studies.

In this manner, the bibliographic-coupling network analysis uncovered two main clusters that present the major research themes of *ergonomics for environmental sustainability* and connect each theme to relevant literature in this domain.

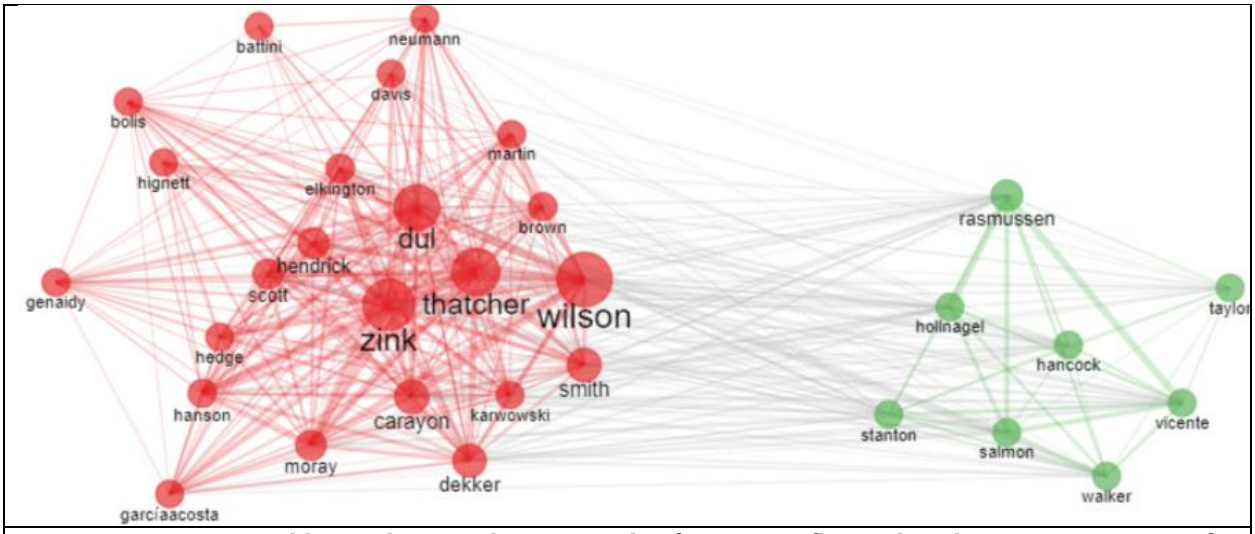

Figure 16 Caption: Bibliographic-coupling network of top 50 influential authors in *ergonomics for environmental sustainability* (2011-2021)

Figure 16 Alt Text: Cluster 1 (Blue) - Largest cluster with 23 authors, among them significant are: *John R. Wilson, Andrew Thatcher,* and *K.J. Zink.*
Cluster 2 (GREEN) - Smallest cluster with 8 authors; among them significant are *Jens Rasmussen, Salmon and Stanton.*

Ethical Statement- Not applicable

3.3 Co-Occurrence Networks

Co-occurrence networks visually map how frequently variables/terms/keywords appear together. This network offers us to study several pairs of co-occurring keywords simultaneously.

3.3.1. Keyword co-occurrence network

A keyword co-occurrence network identifies the primary keywords in the research articles within a specific research domain and helps to reveal the primary themes. Keyword co-occurrences across the different published articles can be generated using various bibliometric fields (such as abstract, title, and keywords). In this study, the R *bibliometrix* package was used to construct the keywords' co-occurrence network as shown in Figure 17. Cluster 1 (Green colour) is the largest cluster within the keyword co-occurrence network and consists of 12 nodes. We observe that the intra-cluster coherence is moderate for this cluster. The top two keywords in this cluster are *human factors* and *sustainability*. Cluster 2 (Blue colour) is the next big cluster in the keyword co-occurrence network and consists of 7 nodes. The top two keywords in this cluster are *ergonomics* and *environment.* Cluster 3 (Red colour) is the smallest in the entire keyword co-occurrence network and consists of 4 nodes. The top two keywords in this cluster are *green ergonomics* and *sustainable development.* These findings answer our third research question (RQ3): *What are the dominant research areas in ergonomics for environmental sustainability?*

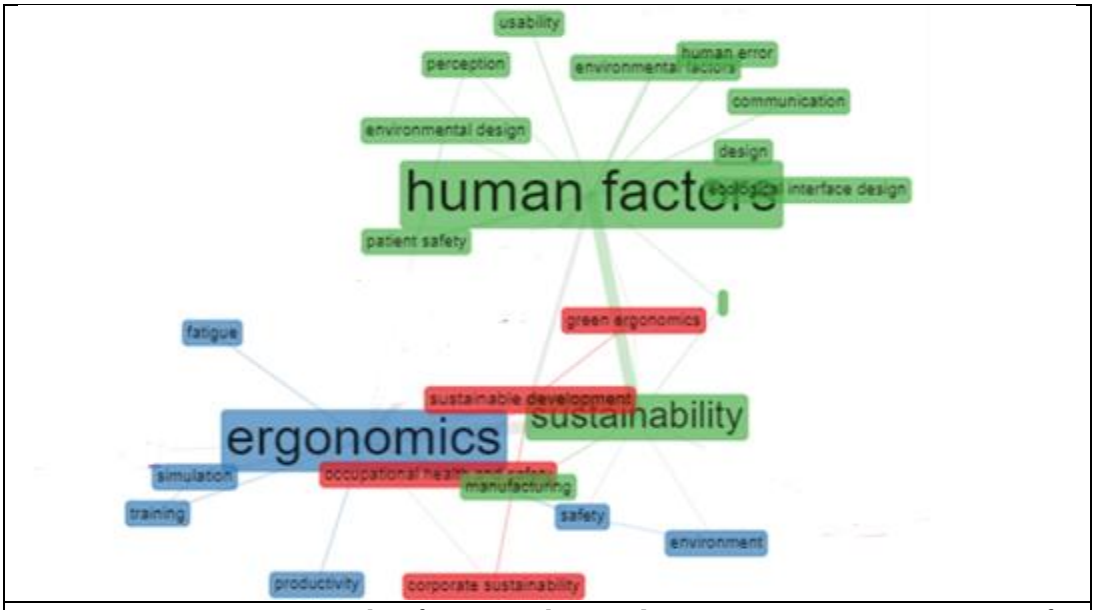

Figure 17 Caption: Network of top 20 keywords co-occurring in *ergonomics for environmental sustainability* (2011-2021).

Figure 17 Alt Text: Network plot representing the co-occurrence of top 20 keywords used in ergonomics for environmental sustainability from 2011 until 2021. The font size of each keyword in the graph is proportional to its frequency of occurrence.

Ethical Statement- Not applicable

3.3.2. Trend of Keywords usage in ergonomics for environmental sustainability

To examine the trend of keyword usage for each year, we identified the count of keywords appearing in the published research articles for each year and presented them in Figure 18. It tells us that the count of the keyword *"human factors"* in *ergonomics for environmental sustainability* has gradually increased until it reached the maximum usage of 24 in 2021. To develop the keyword trend plot, the following keywords: "ergonomics", "human factors", "environment", and "green" were removed from the analysis because these keywords were used for the initial search and extraction of the articles. A few identical keywords were also removed to avoid repetitive plots. We find that the following keywords: "sustainability", "social sustainability", "musculoskeletal disorders", and "occupational health and safety" have been experiencing a recent higher usage among scholars in the area of *ergonomics for environmental sustainability*.

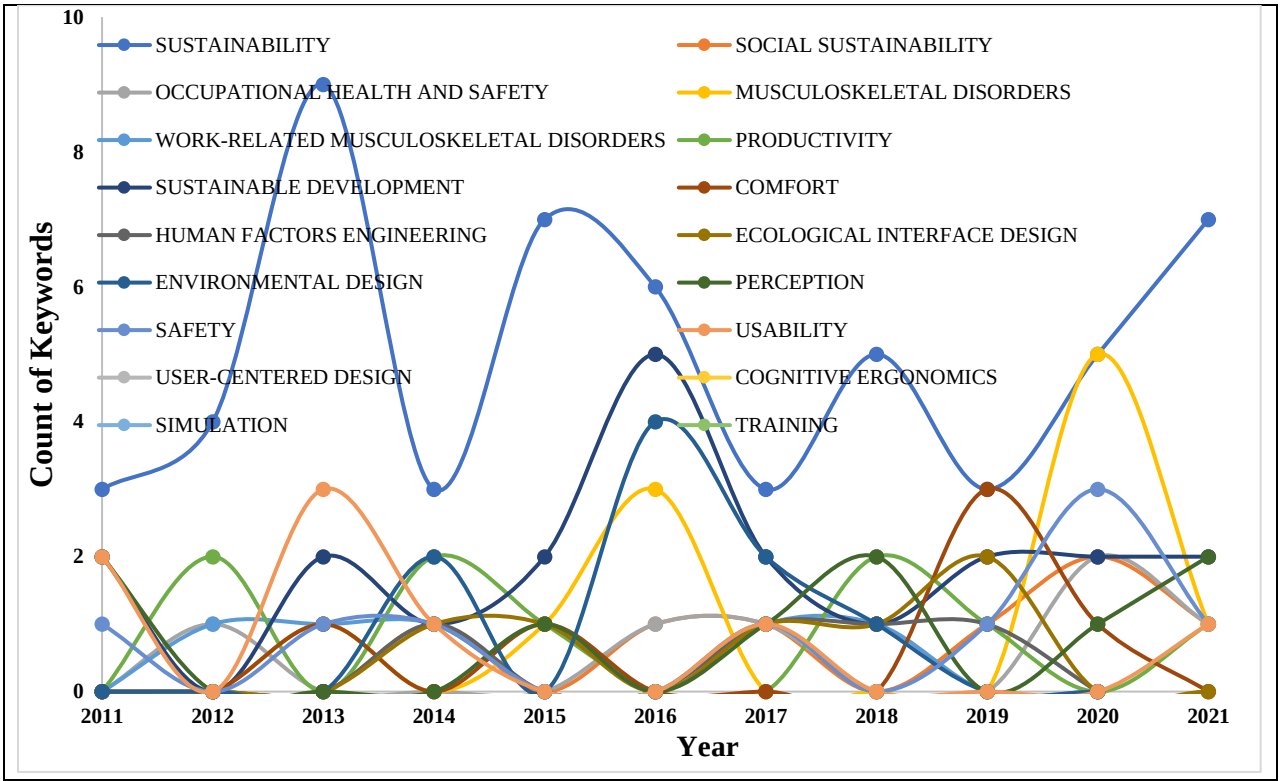

Figure 18 Caption: Trend of Top 18 Keywords in *ergonomics for environmental sustainability* (2011-2021)

Figure 18 Alt Text: Line plot representing the growth of keywords in the domain of ergonomics for environmental sustainability from 2011 until 2021. **Sustainability** (blue colour) is the most used keyword, followed by **social sustainability** (orange colour) and **occupational health and safety** (grey colour).

Ethical Statement- Not applicable

3.4. Generation of conceptual structure map on "ergonomics for environmental sustainability"

This study generates a keyword's conceptual structure map through multiple correspondence analysis (MCA) on the author-keywords used in the 418 published papers. Figure 19 represents the MCA analysis for the associated published research articles between 2011 and 2021, while the concepts are separated into two dimensions. To develop the map, the following keywords: "ergonomics", "human factors", "environment", and "green" were removed from the analysis because these keywords were used for the initial search and extraction of the articles. The first dimension contributes 39.01% of the total variation, while the second dimension accounts for 23.72%. For any MCA-based analysis, the keywords towards the centre signify those which have received greater attention in recent years. In contrast, the keywords nearer to the edge suggest that those study themes have received lesser interest from scholars or have merged with some other themes over time. In addition, the MCA plot reveals three major conceptual clusters – the largest one being RED, followed by two smaller clusters – BLUE and GREEN, as shown in Figure 19.

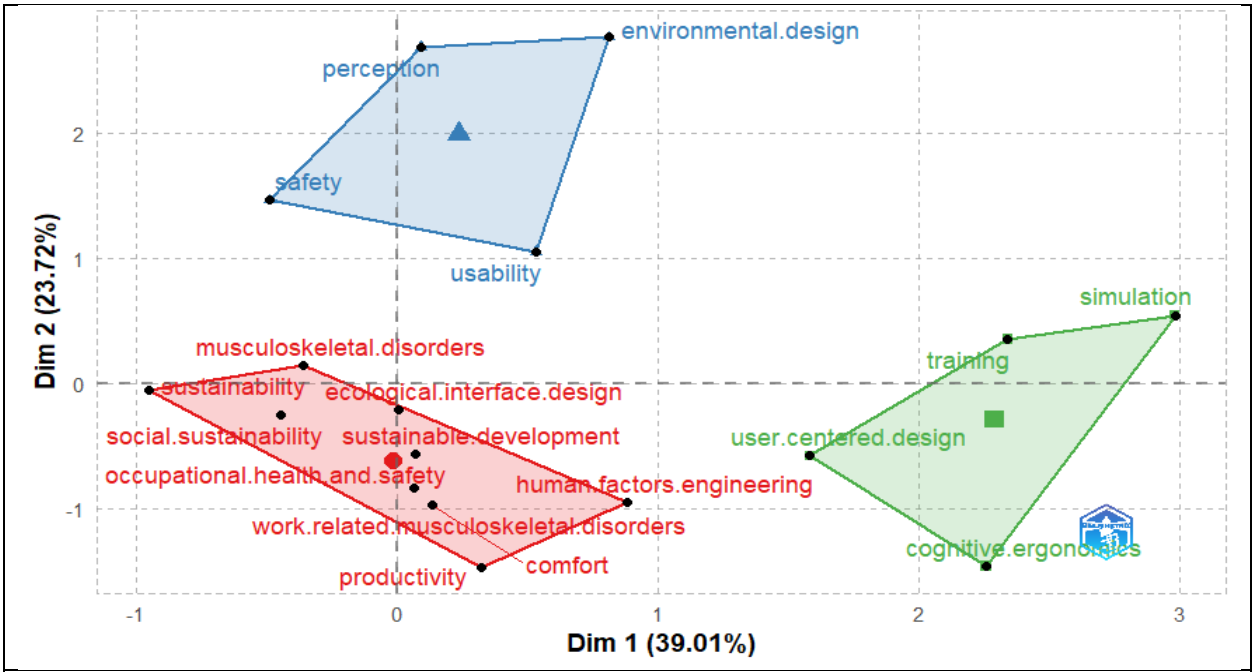

Figure 19: Conceptual structure map of *ergonomics for environmental sustainability* (2011-2021) using Multiple Correspondence Analysis (MCA) technique

Figure 19 Alt Text: a co-word analysis for the domain of ergonomics for environmental sustainability from 2011 until 2021 represented as structural clusters with keywords as nodes. The biggest cluster (red colour) comprises the following keywords –*comfort, productivity, sustainable development,* and *human factors engineering.* Next is the blue-coloured cluster, comprised of four keywords; *Safety, usability, perception, and environmental design*. The third cluster is green coloured and includes the four keywords – *simulation, training, cognitive ergonomics, and user-centred design*.

Ethical Statement- Not applicable

4. Discussion and Findings

Though *ergonomics for environmental sustainability* has gained attention since 2011, we still found a scarcity of research papers published in this area. Our study attempted a thorough bibliometric and network analysis to fill this research gap. It also identified the current trends and patterns of published research articles, influential authors in this domain and their academic research works, and emergent research clusters in *ergonomics for environmental sustainability*.

The significant findings of this study are as follows:

- The literature on *ergonomics for environmental sustainability* has rapidly grown in the number of published articles at an annual growth rate of 6.71% between 2011 and 2021. To summarise, 1421 different authors published an overall 418 papers. These publications received an average citation of 15.72 per publication, while the average citations per document per year were 2.32.
- *Andrew Thatcher* is the most productive with nine publications, and Neville A. Stanton is the most influential author with 313 citations in *ergonomics for environmental sustainability*.
- *USA, Italy, and UK* are the top three countries that published the highest number of research articles. Further analysis shows that scholars from the USA have emerged as significant collaborators with European countries, Brazil, South Africa, Australia and New Zealand. However, scant work has been published by authors from Asia and Africa, except Andrew Thatcher from South Africa, and scholars from these countries have rarely collaborated with any other countries.
- According to the analysis, the University of the Witwatersrand in South Africa is at the top of the list of the most contributing institute with 14 research articles. This ranking was done on the basis number of publications. *Andrew Thatcher*, one of the most prolific authors, is affiliated with this university, and he nurtured and developed this domain from its nascent stage.
- *Applied Ergonomics* is the most prolific journal for research article publications related to *ergonomics for environmental sustainability*, leading to 71 publications.
- The analysis report uncovered three main clusters, with the two most co-*cited papers being Haslam and Waterson (2013) and Thatcher (2013)* in the co-citation network.
- The analysis from the bibliographic-coupling network (author-based) uncovered two clusters. Cluster1 (red) has 23 authors; among them, significant are *John R. Wilson*, *Andrew Thatcher*,

and *KJ Zink*. Cluster 2 (green) with 8 authors, among them significant are *Jens Rasmussen, Salmon and Stanton.*

4.1. Findings from the conceptual structure map

The most compressive cluster (RED) comprises the following keywords – *comfort, productivity, sustainable development, social sustainability productivity, musculoskeletal disorders and human factors engineering (Figure 19).* Previously published articles that used these keywords had similar research topics such as ergonomics/human factors requirements in the eco-design of energy-related products (e.g., Sierra-Perez et al., 2019); design for sustainability: ergonomics – carpe diem (e.g., Martin et al., 2013; Thatcher et al., 2013; Thatcher and Yeow, 2018); human-factors/ergonomics professionals Contribute to global climate change solutions (e.g., Drury, 2014); and sustainable world through human factors and ergonomics (e.g., Zink and Fischer, 2013; Large-Morales et al., 2014).

The GREEN cluster comprises research articles focused on the role of training and cognitive in the design of green building (Hedge, 2010; Hedge and Dorsey, 2013; Smallwood and Saas, 2016), consequences of green building construction on workers' health and safety (Thatcher and Milner, 2012), and design of water management for green building (Kalantzis et al., 2016). These themes are emerging areas of research. Other research areas such as renewable energy, environmental building, and sustainability jointly work on these themes with the help of ergonomics.

The BLUE cluster comprises the four keywords – *usability, perception, safety* and *environment design*. This cluster focuses on the role of ergonomics in the movement towards environmental sustainability (Brunoro et al., 2020).

4.2. Future directions for applied research and practice on ergonomics for environmental sustainability

The thematic contents and network analyses of the past articles were important for us to identify the major dimensions related to "ergonomics for environmental sustainability" published between 2011 and 2021. From a theoretical point of view, a large proportion of the studies (e.g., Zink, 2014; Thatcher & Yeow, 2016a, 2016b) were based on theoretical and modelling perspectives. However, we observed few articles presented empirical work in this domain. This finding indicates that there are many opportunities for future applied research and practice on "ergonomics for environmental sustainability". This finding answers our ***RQ4: What are the avenues for future research areas***

in ergonomics for environmental sustainability? Therefore, we present two future research questions for potential investigation by scholars:

1. What dimensions of "ergonomics for environmental sustainability" would benefit African and Asian countries? How do we compare those dimensions with existing dimensions?
2. How would the COVID-19 pandemic affect the "ergonomics for environmental sustainability domain" worldwide? For example:
    i. Would the COVID-19 pandemic expedite the implementation of "ergonomics for environmental sustainability" and its faster adoption across all dimensions?
    ii. Would the COVID-19 pandemic lead to innovative interventions?
    iii. Would "ergonomics for environmental sustainability" positively or negatively impact the environment and society?

This study also reveals the research collaboration, affiliated countries, and reputed journals in the domain of *ergonomics for environmental sustainability.* It also identifies the impact of journals and research publications on *ergonomics for environmental sustainability*. To our knowledge, this is the first study to apply a bibliometric and network analysis to the emerging area of *ergonomics for environmental sustainability*. We believe that academicians, scholars and experts in this research area will benefit from our study and develop ideas for future research on *ergonomics for environmental sustainability*, as presented later in Table 5.

5. Conclusion and Future Scope

Ergonomics for environmental sustainability has been identified as an imperative but niche research area in ergonomics. The increasing number of publications in this area also validates this argument. This study presents a consolidation of academic research on *ergonomics for environmental sustainability* using bibliometric and network analysis to identify and analyse the recent publication spanning from 2011 to 2021. Through these techniques, we observe that the *ergonomics for environmental sustainability* has exponentially increased with a growth rate of 10.74% between 2011 and 2021. Many articles have been published from the USA, Italy, and UK. The United States is one of the world's largest emitters of greenhouse gasses. As a result, they are more concerned about environmental issues such as climatic change, deforestation, pollution, and waste and proposed many environmental policies. Despite the highest number of papers being published from the USA, Andrew Thatcher from South Africa is the most prolific and influential

author. Therefore, the University of Witwatersrand in South Africa emerged as the most contributing research institute.

Nevertheless, we notice that *ergonomics for environmental sustainability* received less attention from African countries (i.e., Botswana, Kenya, and Tunisia) and Asian countries (particularly India, Bangladesh, Maldives, and Sri Lanka). This study has a few limitations. First, the dataset in this study considers research articles from 2011-2021, and this dataset was restricted to Scopus only. Future scholars might plan to combine multiple data sources and build a more comprehensive analysis. Second, bibliometric data sources (such as Scopus) were not primarily made for bibliometric research. Therefore, some data-cleaning errors might still be present. Third, although rich, bibliometric insights remain inadequate; in particular, they do not reveal theories and methods used in the research domain. Future scholars might combine literature reviews with bibliometric analyses to create a more robust state-of-the-art review for a domain.

Ethical Statement- Not applicable

Table 5. Summary of suggested research directions

Dimensions	Gaps/issues	Research directions
Design	Lack of ergonomics framework in the design area for addressing the environmental issues and lack of qualitative studies	1. There is a need for study and design to reduce the weight of boxes, bins, and collection vans in the recycling industries. 2. Presently, biomimetic design is not incorporated with ergonomics. Therefore, there is a demand to explore the research opportunities in biomimetic design applied to ergonomics. 3. Design for improving waste management and recycling process 4. Need for design to error prevention to thwart environmental disasters 5. Several research opportunities for ergonomics intervention to reduce fuel wastage through task analysis. 6. United States Green Building Council revealed several opportunities in workstation design for green building construction such as schools, offices, and retail buildings to reduce musculoskeletal injuries among the occupants
Green Job	Less implementing framework and effective awareness plan for manual handling jobs	1. Ergonomics should be integrated into the design of green jobs in several industries such as recycling and the renewable energy sectors to offer a deep understanding of required behaviour changes to become a sustainable society. 2. Need for an awareness plan and implementation framework in manual handling jobs of renewable industries for operational managers to reduce the musculoskeletal disorder risks.
Green organisation	Traditionally focus on organisation and firm	1. Determine the effect of work-rest cycles that integrate nature and the positive impact of time spent in nature and its impacts on productivity and well-being in the traditional office environment. 2. Apply organisational ergonomics perspective in global supply chain and social life cycle assessment to ensure that environmental issues are adequately resolved across the entire process.

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Dimensions	Gaps/issues	Research directions
Theories	Most current theoretical frameworks are drawn from systems design, systems theories, HFE theories	1. Deepen the application of extant theories. 2. Borrow applicable theories from other fields of knowledge such as "systems design" in information systems or the engineering disciplines. For instance, the "design science paradigm" could be an interesting way to look at ergonomics, which would also improve the current number of low application-oriented articles in "ergonomics for environmental sustainability", also reported by Bolis et al. (2022). 3. Possibly use multiple theoretical lenses to explain a complex phenomenon. 4. Develop new theories in the "ergonomics for environmental sustainability" domain.
Focus of publications in journals	The current body of knowledge in "ergonomics for environmental sustainability" is much restricted to a niche group of journals only (see Figure 11)	1. Disseminate the concept of "ergonomics for environmental sustainability" to a much wider community of scholars. 2. Scholars should target journals in other areas that could possibly embrace the topic of "ergonomics for environmental sustainability" such as supply chains, human resource management, organisational design, manufacturing and service operations, transportation research, general business and management, systems design in information systems, green entrepreneurship, business process modelling to name a few.
Application and practice-orientation	Few empirical articles and case studies	1. Build more comprehensible datasets 2. Create 3. Survey and questionnaire-based study

Ethical Statement- Not applicable

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Ethical Statement- Not applicable

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