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Bibliometric visualization of metal-air battery research trends

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ABSTRACT

Metal-air batteries are rechargeable secondary batteries with high energy density, typically using carbon electrodes. However, carbon waste poses environmental risks. Fly ash, a byproduct of coal combustion, offers a sustainable alternative due to its high electrical conductivity. This study analyzes research trends on metal-air batteries and fly ash from 2019 to 2023 using bibliometric visualization of Scopus-indexed publications. The keyword search was refined from 'Battery' to 'Air Battery' and, finally, 'Air Battery' with 'Fly Ash,' yielding 60 relevant articles. Using the VOSviewer, research patterns, key focus areas, and collaboration networks were identified. The results indicate a 14.87% increase in publications from 2019 to 2023, with significant growth from 2019 to 2021 before declining after 2022. This fluctuation suggests shift in research interests toward other battery technologies. Fly ash demonstrates potential as a carbon substitute for air batteries, promoting sustainability. However, further research is needed to optimize its application and address technical challenges. Bibliometric visualization highlights a growing interest in fly ash for environmentally friendly battery development due to its abundance and sustainability.

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1. INTRODUCTION

A battery is a device that stores electrical energy in the form of chemical energy and then converts it back into electrical energy when needed. This is a perfect example of the principle of energy conservation, where energy cannot be created or destroyed, but can only be converted from one form to another. In the context of engineering philosophy, batteries can be considered a symbol of how technology can be used to control and manipulate nature for the benefit of humans. Battery technology allows us to store energy in a form that can be used anytime, anywhere, and in the amount we want. This is an example of how technology gives us the power to change the way nature works.

Today, in order to achieve decarbonization, effective energy storage technology is very important. Batteries, as one of the most flexible electrochemical energy storage systems, have the potential to bring the world out of the current climate crisis towards a sustainable and carbon-neutral future [1]. The main problem is that there is still a lack of environmentally friendly batteries and a large supply of raw materials [2]. Batteries operate on a chemical principle called redox reaction, or reduction-oxidation reaction. In this reaction, one material (electrode) releases an electron, a process known as oxidation, while another material (another electrode) accepts the electron, a process known as reduction. Generally, lithium metal is the ideal electrode material, but this lithium metal has a drawback because it tends to settle irregularly so that it will form dendrites that grow across the cell. This will trigger a serious security hazard [3].

The principle of operation of the battery, in more detail, is as follows: The anode is the negative electrode in the battery. When a battery is used to conduct an electric current, the anode undergoes an oxidation reaction, releasing electrons into the circuit. The cathode is the positive electrode in the battery. The electrons released by the anode are eventually accepted by the cathode, in a process known as reduction. An electrolyte is a medium that facilitates the flow of ions between the anode and the cathode. Electrolytes are usually liquids, gels, or solids. An external circuit is a circuit that connects the anode and cathode. Electrons flow through this circuit from the anode to the cathode, providing energy to the device powered by the battery. The chemical reactions that take place in the anode and cathode produce a flow of electrons, which creates an electric current. This reaction may reverse when the battery is recharged.

Batteries come in two types namely primary batteries and secondary batteries are two different types of batteries based on their ability to be recharged. Examples of secondary batteries include lithium-ion batteries, nickel-cadmium (NiCd) batteries, and nickel-metal hydride (NiMH) batteries. The main difference between primary and secondary batteries is the ability to be recharged. Air batteries belong to the secondary battery type.

An air-metal battery is a type of electrochemical cell in which air is reduced and metal is oxidized [4]. The anode in an air-metal battery comes from metals, it can be alkali metals such as lithium, potassium, and sodium, or it can also be alkaline earth metals such as calcium and magnesium, as well as some metalloids such as Si and Al elements or transition elements such as zinc and iron. The constituent electrolyte can be a hydrate or a non-hydrate, depending on the type of anode used. Air, anode, and cathode are other reducing electrodes separated by separators. The air cathode is an unlimited source of the environment and does not need to be stored, so the air metal battery is a different way to store energy [5]. An air battery, also known as a metal-air battery, is a type of primary battery that connects a chemical reaction between metals and oxygen from the air to generate electricity. These batteries have a metal anode and an air cathode [6]. The metal anode will react with the oxygen in the air which serves as a cathode. This reaction will produce an electric current.

An air battery is a type of battery that uses oxygen from the air as one of the electrode materials. Metal-air batteries have two main features. The first is a high-energy-density metal anode coupling, and the second is an open-structure catalytic cathode that continuously draws oxygen from the atmosphere [7]. Higher energy density of battery electrode material type, the metal-air battery has the highest advantage (3-30x) over the lithium-ion battery [4]. Although high energy density is the main advantage of air batteries, elements such as anode materials and electrolyte problems somewhat limit their application. The limitation is the growth of dendrites on the anode after long use. An air battery is composed of a main core in the form of an air electrode, electrolyte, and the overall design of the battery. When a battery is connected to a complete circuit, the chemicals inside it undergo a chemical reaction, which releases currently from one terminal to another [8]. The open-cell air electrode structure in a metal-air battery recharge system allows redox reactions between active metal materials and oxygen gases available from the air. The advantage of metal-air batteries lies in the fact that only these active metals should be stored in the battery system [9].

In general, air batteries use carbon as the electrode material in the battery. At the same time used in air batteries is an aqueous solution saturated with metal hydroxide or metal chloride. Metal anodes are unstable in aqueous solutions, so there needs to be a watertight material as a separator between the anode and the aqueous electrolyte. This means that the air electrode must have sufficient porosity so that air can penetrate from the environment and be waterproof so as to prevent electrolyte leakage [8]. Although carbon waste material air batteries can be used as an alternative energy source, the fact is, the manufacturing process and use still have the potential to pollute the environment. This is due to the greenhouse gas emissions produced during the production and use of the battery. In addition, these batteries can also generate hazardous waste if not recycled properly. Therefore, it is important to continue to conduct research and development in order to create more environmentally friendly battery technology [10].

Recent research suggests that fly ash can be used as a carbon substitute in the manufacture of these batteries. Fly ash is a solid waste produced from the combustion of coal and contains toxic heavy metals such as lead (Pb), copper (Cu), cadmium (Cd), mercury (Hg), and zinc (Zn), making it hazardous waste [11], [12]. Fly ash has the potential to substitute carbon in the manufacture of air batteries. Fly ash has an ideal shaft structure for this application and also has good electrical conductivity, which is an important requirement for battery electrode materials. Thus, the use of fly ash as a carbon substitute material in the manufacture of air batteries can be an innovative solution to reduce coal waste and also produce more environmentally friendly batteries. Zhang *et al*. [13] said that to make Si-based composites that are very stable, cheap, and easy to prepare, fly ash can be used because the residue is not flammable as it consists of fine particles. Fly ash with a high silicon-based material content can function as an anode for lithium-ion batteries. The water-holding capacity and surface area of this coal fly ash make it suitable for use as a sorbent to remove H2SO4 fog from lead-acid battery factories [14]. The metal content in fly ash in the form of Al2O3 and Fe2O3 as lithium-ion battery materials, namely cathodes, needs to be considered for the development of energy storage technology in the future [15]. Some of these studies show that, so far, there have been studies that have examined the use of fly ash as a material that makes up air batteries (cathodes).

This analysis aims to analyze the research trends of metal-air batteries and fly ash in 2019-2023 from articles published in Scopus indexed journals using Bibliometric visualization. The benefit of this analysis is to find out the development of air battery and fly ash research that has been researched by researchers in the world, including its relationship with other variables studied during 2019-2024, so that the data obtained can be used as a basic reference in the development of air and fly ash metal battery research in the future. Several studies have explored the potential of fly ash as a carbon replacement material in metal-air batteries, although the existing studies are still limited to laboratory experiments or specific case studies. Until now, there has been no study that systematically maps the global research trends related to metal-air batteries and fly ash utilization using bibliometric methods. Therefore, this study aims to fill this gap by analyzing publication trends, researcher collaborations, and key research focuses in the last five years. This study provides broader insights for researchers and industries in identifying further research opportunities and strategies for developing more sustainable battery technologies. Despite the growing body of research on air batteries and the use of fly ash, a comprehensive bibliometric analysis that maps global research trends, key contributors, and collaboration networks remains limited. Most previous studies have concentrated on the experimental use of fly ash as an electrode material, yet a systematic review of its research evolution over time is still lacking. This study seeks to bridge that gap by examining research trends in metal-air batteries and fly ash from 2019 to 2023 through bibliometric visualization. The primary goal is to highlight key research patterns, major focus areas, and global collaborations, providing a strong foundation for future advancements in this field.

2. METHOD

Research data was collected from Scopus by entering the keywords "air battery" and “fly ash” in the title, keywords, and abstract (field of discipline). The collected data is then analyzed and visualized using VOSviewer visualizations to identify research trends, author collaborations, and key focus areas. This method can provide an overview of research developments, focus areas, and collaboration networks in the field of air batteries. In more detail, the stages of the bibliometric analysis method are illustrated in Figure 1.

Figure 1 explains that the first step begins with conducting a keyword search, which in this study initially used the keyword “battery” for all research years. The first keyword is still very broad, so keyword development is carried out so that the research articles collected are in accordance with what is expected. Keyword selection was done in stages to ensure that the study specifically examines trends in metal-air batteries. The initial focus on “battery” resulted in a very large number of publications that were less relevant to the research objectives. Therefore, a narrowing down to “air battery” was done to filter only studies discussing air-based batteries. Furthermore, the keyword “fly ash” was added to identify studies exploring the utilization of coal waste as a material in this type of battery.

Figure 1. Stage of bibliometric analysis

Then the keyword was narrowed down by changing it to an air battery type and the research year was narrowed down to the last 5 years (2019-2023), so that the keyword changed from "battery" to "air battery" and all research years became the research years 2019-2023. After that, enter the keyword refinement stage. At this stage, the keyword "air battery" is combined with the keyword "fly ash" with the same research years (2019-2023). The final results at the stage of development and refinement of the search for research articles through these keywords resulted in as many as 60 research articles which will be continued at the data analysis stage. The results of each stage of the bibliometric analysis are illustrated in Figure 2.

According to Figure 2, initially, the search for articles was carried out from all years with the keyword "battery" and obtained an output of 507,315 articles related to batteries. Then, the keyword is narrowed down to the years 2019-2023 with the word "air battery". The number of research articles that analyzed water batteries was found to be as many as many as 195 research articles. After that, the keyword "air battery" was perfected by adding a third keyword, namely "fly ash" with the same year range, namely 2019-2023. The output of the two main keywords shows as many as 60 research articles.

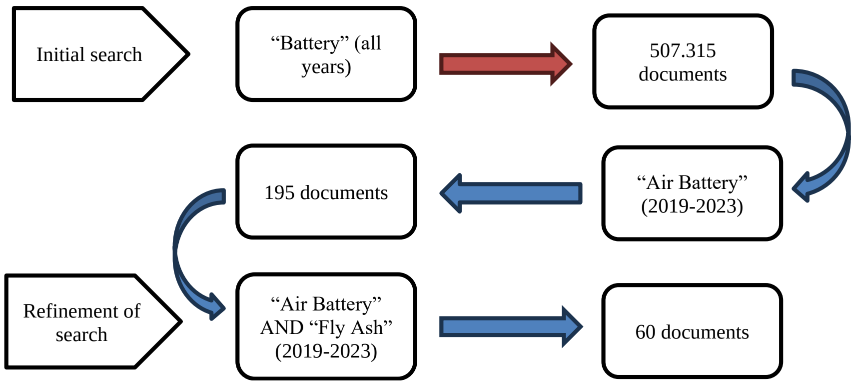

Figure 2. Illustration of keyword search and refinement

The data that has been collected as many as 60 research articles are then analyzed to identify emerging research patterns and developing research focuses. Visualization using software such as VOSviewer helps in visualizing research networks and identifying key contributors in the domain of air battery research. As such, this approach allows researchers to gain in-depth insights into research developments, evolving research trends, and future research opportunities in the airborne battery domain. This data is available in (.ris) and (.csv) formats and is then processed using a variety of programs for bibliometric and network analysis, including Microsoft Excel and VOSviewer. Simultaneous keyword emergence analysis was also carried out using the VOSviewer, which uses the visualization of similarity (VOS) algorithm as an alternative method for multidimensional scaling.

This study uses VOS clustering because the VOS clustering method is specifically designed to be able to perform bibliometric analysis by considering the semantic proximity between keywords based on relationships. The VOS algorithm is superior when compared to other methods, such as the k-means clustering method, because it does not require a predetermined number of clusters. VOS algorithms are also more effective at handling large-scale networks with complex relationships between publications. To ensure accurate and meaningful clustering, the main parameters in VOSviewer are configured as follows:

- The threshold for the number of occurrences of a keyword is determined based on a minimum threshold of occurrences (e.g., 5 times) in order for a sufficiently significant term to be included in the analysis.
- Normalization method with association strength to ensure that the association between terms is calculated in proportion to their total distribution in the dataset.
- The resolution of the clustering to avoid the collision of clusters that are too large or too small while ensuring that each group represents a fairly specific subtopic in metal-air batteries and fly ash research.
- The size of the nodes and edges is set according to the number of occurrences and frequency of linkages to make them look more dominant in the visualization.

The configuration is to ensure that the clustering results obtained not only visually represent the relationship between keywords but also reflect the conceptual structure of the developing research. In order to ensure the reliability of the results, a comparative analysis of the resulting patterns with research trends that have been known in the previous literature is carried out so that the results are in harmony. Sensitivity tests are also carried out by making changes to the resolution parameters and threshold number of occurrences so that the cluster pattern is stable and does not depend on a specific configuration. The VOS mapping technique shows good performance compared to other mapping techniques that produce distance-based maps. VOSviewer is capable of producing a sizable scale map that can load more than 5,000 items and co-site maps in a fairly short time [16].

During the analysis using the VOSviewer, the bibliometric data collected from Scopus, which was stored in the RIS format (.ris) before extraction, data normalization and data filtering were carried out. The goal is to make the data used relevant according to the specified criteria. After that, identification and extraction are carried out on important features in the article that have been collected, such as keywords and titles. Then, a bibliometric analysis was carried out by analyzing the collaboration between authors and identifying the relationship between documents according to the same keywords "air battery" and "fly ash" to the creation of the linkage matrix. The results of the matrix are visualized with VOSviewer to create a network map that connects elements in the data for interpretation of the results to identify significant patterns, relationships, and trends.

3. RESULTS AND DISCUSSION

3.1. Publication search results

The results of a data search from Web Scopus with the query TITLE-KEY-ABS ("battery") using the keyword "battery" show the number of publications reaching 507,315 publications in all years in all years (first year - 2024). Furthermore, with the query TITLE-ABS-KEY ("air battery") AND PUBYEAR > 2019 AND PUBYEAR < 2023, there are 195 publication articles. Then, with the query (TITLE-ABS-KEY ("battery") AND TITLE-ABS-KEY ("fly ash") AND PUBYEAR > 2019 AND PUBYEAR < 2023, there are 60 publications shown in Figure 3. The 2019-2023 period was selected to examine the development of trends and research patterns in air batteries and fly ash over the past five years.

Based on the keyword search carried out, the results provide a broad overview of the research that has been carried out in various contexts related to batteries, air batteries, and fly ash ranging from the development of battery technology to applications in various industries. This data is an important basis for understanding the evolution of research on batteries and the trends that may emerge over time. A significant number of publications, the results of this search show how important batteries are as a constantly evolving and relevant research subject in various fields of science and industry.

In order to understand the growth dynamics in the "air batteries" study, analysis was also carried out by calculating the compound annual growth rate (CAGR) in the 2019-2023 period, as in the data obtained through Figure 3, as follows.

$$CAGr = \left(\frac{V_{final}}{V_{initial}}\right)^{\frac{1}{t}} - 1 = \left(\frac{8}{4}\right)^{\frac{1}{5}} - 1 = 0{,}1487 = 14{,}87\%$$

Based on the analysis of publication trends from 2019 to 2024, the number of publications "air batteries" experienced an average annual growth of 14.87% according to the results of the compound annual growth rate (CAGR) calculation that has been carried out. A significant increase occurred from 2019-2021 which then decreased after 2022. This trend indicates that there is a fluctuation in research interest in "air batteries" which may be due to the change in research focus to other battery technologies.

3.2. Research trends and publication distribution of air batteries

The analysis of bibliometric data carried out resulted in the following air battery research trends. Based on the number of publications between countries (Figure 4), the publication "air battery" is dominated by China with a total of more than 5500 publications from 2019 to 2023. The United States dominated second with more than 500 publications and South Korea dominated third with more than 490 publications. Then Australia, India, Japan, Germany, Canada, Hong Kong, and Singapore dominate with more than 400 publications, but not more than South Korea. The ten countries mentioned are the countries that have contributed greatly to the research of air batteries.

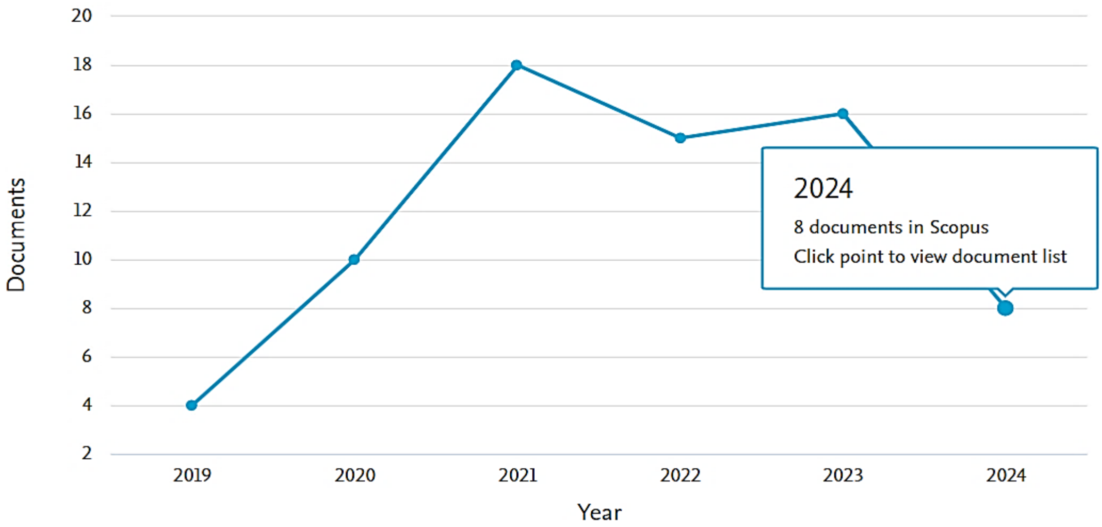

Figure 3. Search results for publications "air batteries" in 2019-2023

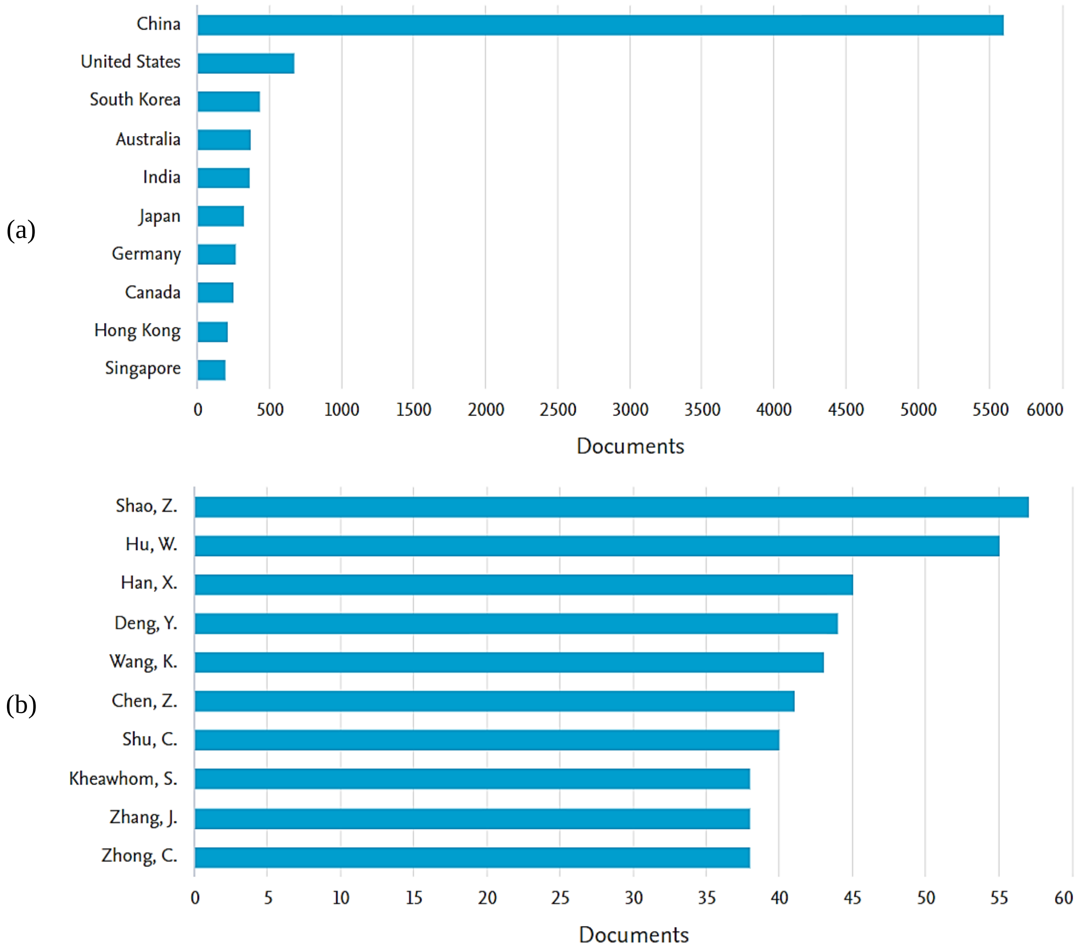

Figure 4. Publications "air battery" (2019-2023): (a) between countries and (b) by author

One of the main limitations of the Scopus-based bibliometric approach is the potential bias in the representation of global research. Scopus tends to over-list journals published in English and from countries with wider academic access, such as the United States, Europe, and China. As a result, research from developing countries published in other languages or in local journals may be under-represented in this analysis. Furthermore, not all journals are open access, so studies with restricted access may not be fully captured in this analysis. According to [17], who compared document coverage between Scopus and Dimensions at the country and institution level, found that there were differences in document coverage that could affect bibliometric analysis and highlighted the importance of selecting appropriate databases to avoid bias. The solution can be done by adding additional databases, for example, by combining databases from Scopus with Google Scholar, Dimensions, Lens.org, and CrossRef to obtain a wider coverage of research from developing countries. The research also provides suggestions to encourage indexation of local journals on Scopus or the Web of Science to be globally accessible. Brück [18] highlighting the lack of representation of authors from developing countries in leading journals, the results found that institutions in developed countries are more likely to be correspondent authors so that they can reflect geographical inequalities in scientific publications. In addition, developing countries also have limited access to research funds and international collaboration networks. The study recommends encouraging international collaboration between researchers from developing countries and researchers in developed countries so that more research can be published in reputable journals. Developing countries also need to increase research funding so that academics have the same opportunities for publication in international journals. But if access to reputable journals is limited, researchers can publish their research results on Preprint Servers such as arXiv, SSRN, or ResearchGate to increase the visibility of their research. Asubiaro *et al.* [19] highlighted the representation of journals in the Web of Science and Scopus by geographic region and found that there was a significant disparity. Journals from developed countries are more dominant than developing countries, which can indicate potential bias in bibliometric analyses that use these data. The study also suggested using additional databases, as in the study

[17]. The study also suggested that bibliometric analysis include research in multiple languages to ensure that research that is not published in English can be included in the analysis. Then, when comparing results from various databases, it is recommended to use data normalization to ensure that the results of the analysis are more accurate and do not only reflect publication trends from one region or language only.

The distribution of "air battery" publications when reviewed by country (Figure 4(a)) shows that China has a very abundant distribution of publications, more than 5,500 publications, followed by the United States and South Korea. Judging from the authors who are most prolific in researching air batteries (Figure 4(b)), it shows the 10 most researchers in air battery research in 2019-2023. The most authors with 57 air battery publications were written by Shao, Z.; Hu, W. as the second author with 55 publications; and Han, X. as the third most authors with 45 air battery publications. Meanwhile, Deng, Y., Wang, K., Chen, Z., Shu, C., Kheawhom, S., Zhang, J., and Zhong, C. are next with ≥ 38 publications. Based on the type, the distribution of air battery publications in the world is 85.8% in the form of research articles, 9.9% in the form of review studies, and the rest in other forms, such as conference papers, book chapters, and so on are shown in Figure 5(a). Judging from the source, the publications that contain the most air batteries are in material science (23%), chemistry (22.1%), chemical engineering (13.8%), and the rest are as shown in Figure 5(b).

Based on mapping and visualization from publications related to the relationship between air batteries and types of air batteries in the world, namely researchers who raised lithium-ion batteries, namely Arnaiz *et al.* [20], raised the research needs for the development of efficient and durable energy storage solutions for Li-ion batteries by using dilithium squarate (Li2C4O4) to improve the performance of lithium-ion capacitors. Marangon *et al.* [21], Lee *et al.* [22], and Tao *et al.* [23] propose the use of silicon-core-carbon nanocomposites synthesized through liquid salt-based rice husk reduction to improve battery performance and life Li-ion. Rodrigues *et al.* [24], Wu *et al.* [25], Wen *et al.* [26], Cui *et al.* [27], and Yu *et al.* [28] propose the use of graphene produced through the mechanochemical ball milling process as an anode for Li-ion batteries. While Kim *et al.* [29] propose the use of MoO2/C composites and Bhujbal *et al.* [30] propose SiO/Gr on the electrode to improve the capacity and cycle stability of the anode of graphite-based Li-ion batteries. The use of graphite as an anode material and cathode from cobalt (LiCOO2) to nickel to maintain the complexity and uncertainty of lithium-ion battery prices in the future [31]-[34]. Guan *et al.* [35] also offer a solution to overcome the problem of decreasing capacity and short battery cycle life by using surface coating techniques on cathode materials with Al2O3, TiO2, and Li2SiO3. While Chiku *et al.* [36] offer the development of carbon composites and various forms of manganese oxide (amorphous MnO2, crystalline α-MnO2, and Mn2O3) to overcome the low discharge capacity and limited charge cycles of Li-ion batteries.

Related to Li-ion batteries and their environmental impact, García *et al.* [37] offer solutions for the use of water-based bonding materials such as Na-CMC and Na-alginate for more environmentally friendly anode electrodes. In contrast to the study, Kaiser and Bringezu [38] dan Darmansyah *et al.* [39] offer solutions for the use of biotest batteries to reduce the environmental impact of hazardous metal waste for aquatic and terrestrial ecosystems. But this solution is still not strong to implement due to the lack of testing methods and evaluation parameters in various countries.

The relationship between air batteries and zinc-ion batteries (Figure 6(a)) and aluminium-air batteries (Figure 6(b)) shows that the research trend as much as it discusses battery performance, catalysts in batteries, and stability in those batteries. Hydrated zinc-ion batteries are also inseparable from the spotlight in air battery research in the world. Lu *et al.* [40] highlight the limitations of the use of the battery in terms of low air recharge cycle stability by using a new organic cathode material such as (1H-1,2,4-triazolil) hexaazatriphenylenecarboxytriimide (TTA-HATTI), which is able to store Zn2+ and H+ and can be oxidized by O2 from the air. This material allows the AZIB to be recharged with air without an external power source. While Lu *et al.* [41] highlight the low energy efficiency, poor cycle stability, and low depth of discharge in rechargeable Zn-water batteries can be overcome by the development of efficient bifunctional catalysts for oxygen reduction (ORR) and oxygen evolution (OER) reactions, as well as the improvement of zinc anode stability through interface engineering, heteroatomic doping, and the development of ion filter layers to reduce side reactions such as hydrogen evolution.

Magnesium-ion batteries researched in research Sun *et al.* [42], Sun *et al.* [43], Chai *et al.* [44], and Ding *et al.* [45] related to the performance and stability of the battery. Secondary batteries formed from zinc-water and aluminum-air batteries are also in the spotlight. Fan *et al.* [46], Lin *et al.* [47], Meng *et al.* [48], and Shahzad and Cheema [49] highlight the problem of dendrite formation in zinc anodes that cause short circuits, side reactions (hydrogen evolution), and corrosion that can reduce the efficiency and stability of the battery cycle. Meanwhile, the management of aluminum-air batteries is carried out by research Chen *et al.* [50] and Sheng *et al.* [51] which develops an equivalent circuit model of an aluminum-air battery that is affected by ambient temperature to obtain the real-time output voltage and SOC of the battery more accurately. Another type of secondary battery that has become a topic of research in the world is the type of sodium-metal battery discussed in the research Zhao *et al.* [52] and Huang *et al.* [53], and sodium-ion batteries discussed in the study by Pinjari *et al.* [54] and Kuai *et al.* [55].

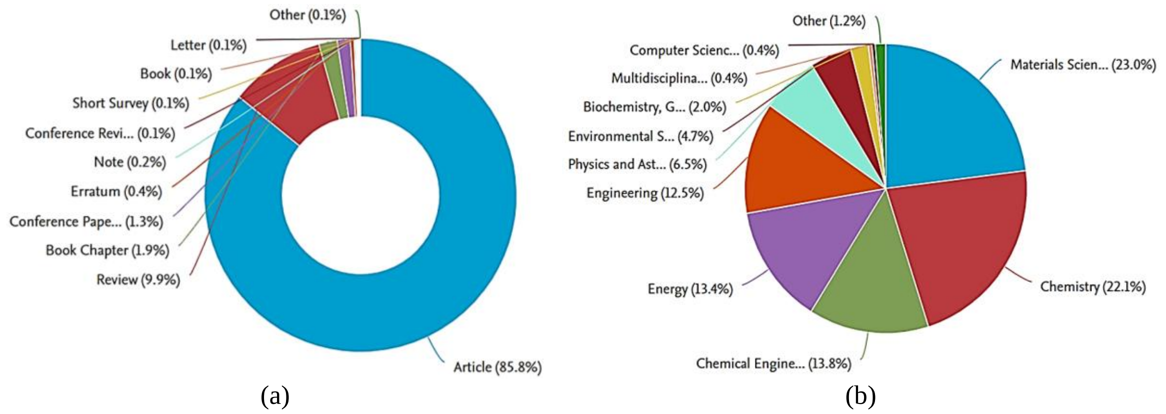

Figure 5. Publication "air battery" by type and source of publication 2019-2023:
(a) publication type and (b) publication sources

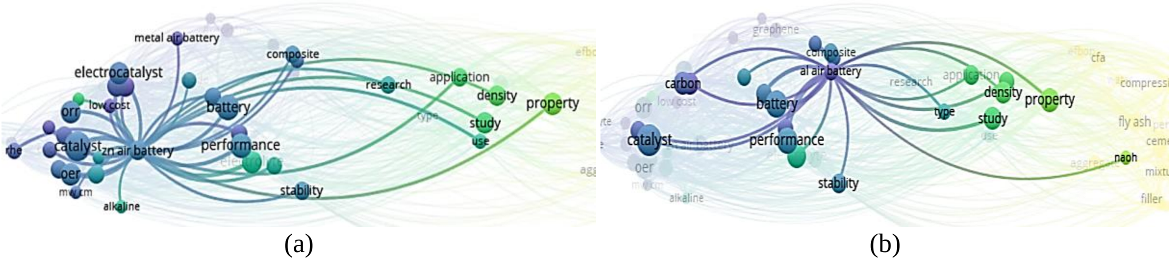

Figure 6. Visualization of publications between batteries in 2019-2023: (a) air batteries and Zn-air batteries and (b) air batteries and aluminum-air batteries

3.3. Research trends and publication distribution of air batteries and fly ash

The research trend of air batteries and fly ash in 2019-2023, based on the number of documents between countries (Figure 7(a)), air battery and fly ash publications are dominated by China, with 37 publications in 2019-2024. India and the United States dominate the second with 15 publications each. Indonesia dominates in third place with 12 publications. Japan ranks fourth with 11 publications. Meanwhile, Portugal, South Korea, Taiwan, Turkey, and Germany contributed 5-8 publications. The ten countries mentioned are the countries that have contributed greatly to air battery and fly ash research in the world in 2019-2023.

Some of the factors that are likely to make China have the highest number of publications as shown in Figure 7(a) because China has implemented aggressive policies in the development of clean energy and battery technology through various national initiatives, for example through the "made in China 2025" and "dual carbon goals" programs that encourage increased investment in battery research and development in China. As explained in the "Guide to Chinese Climate Policy 2022 in section 21: Clean Energy R&D" that the Chinese Government has spent $4-6 billion annually on clean energy research and development (R&D). The International Energy Agency (IEA) found that energy patents in China have increased drastically every five years since 2000, one of which is low-carbon energy patents in battery manufacturing [56].

In addition, the Chinese government also provides large subsidies to research institutions and companies in the field of new energy. China also has a highly developed battery industry ecosystem such as CATL and VYD leading the way in the global battery market, so the industry is closely collaborating with academics on new battery research, including the utilization of fly ash as an alternative material. Universities and research institutes focused on advanced energy and materials technologies in China are also numerous and they have extensive access to funding and laboratory facilities that support their innovations. China has dominated the global Li-ion battery supply chain and is projected to maintain that position of dominance until 2050. China has spent decades building domestic infrastructure such as its battery manufacturing facilities, lithium mining, and processing facilities. Even to be able to compete with China, companies in the US and EU are adopting strategies based on horizontal integration by developing capacity at certain levels of the battery supply chain, such as battery manufacturing and battery anodes [57]. Chinese battery giant CATL and other

Chinese battery manufacturers are active in Europe, where Chinese, Japanese, and Korean battery manufacturers have accounted for nearly half of the planned battery manufacturing capacity through 2030 [58].

China's dominance in "air batteries" research shows that the Chinese state will play an important role in determining the direction of the development and commercialization of metal-air battery technology. If this trend continues, material standards, production methods, and even recycling policies are likely to be influenced by research results from China. This will of course provide the possibility that the global supply chain will be affected. As in the study [59] that it is a fact that European scientists are at the forefront as the most prolific writers. This is expected to be due to the full support provided by the Chinese government for scientific research. Meanwhile, according to [60], the lack of representation of researchers from developing countries is due to shortages in research skills, English language skills, scientific networks, and access to research funding and grants. But it is likely that such a lack of representation is the result of a culture of exclusivity.

The number of publications on air batteries and fly ash in 2019-2023 based on their affiliation (Figure 7(b)) shows that Indonesia is ranked first, represented by Sebelas Maret University with 7 publications. The second position is occupied by the Ministry of Education of the People's Republic of China with 5 publications. Then followed by Zhengzhou University, Universidade de Coimbra, Universidade de Aveiro, A James Clark School of Engineering, and University of Coimbra with 4 publications each. Meanwhile, the bottom three are occupied by the Central Metallurgical Research and Development Institute, the Technical University of Denmark, and New York University which each has 3 publications on air batteries.

Sebelas Maret University has a strong commitment to renewable energy research and sustainable materials by developing various research centers that focus on the use of industrial waste, including fly ash in clean technology applications. Collaboration with companies in the field of energy and materials manufacturing also allows the resulting research to be more applicable and oriented to real-world implementation. Sebelas Maret University is actively researching the use of fly ash as an alternative electrode material. This is in line with the national policy in reducing coal industry waste and pouring more environmentally friendly energy solutions with local resources. Although Sebelas Maret University is the most prolific institution in research on air batteries and fly ash, Figure 7(b) also shows that the University of Indonesia and the Bandung Institute of Technology also contribute to the development of battery technology in Indonesia. The dominance shown by Sebelas Maret University may have implications for the institution's role as an innovation center in industrial waste-based battery technology in Indonesia.

Based on the results of the analysis, Sebelas Maret University (Indonesia) is the most productive institution in the field of air battery and fly ash research, while China plays an important role in distributing research through international networks. Collaborations between universities in the United States and Europe focus more on aspects of materials science and electrode optimization. Based on the collaboration network, countries with strong battery industries such as China and South Korea are more involved in technology-based research and industrial applications while other countries focus more on fundamental and sustainability aspects. Although international collaboration is likely to increase, several obstacles are likely to occur in this global research cooperation. The main ones are limited access to data and research infrastructure in developing countries and regulations related to fly waste. In the future, increased international cooperation in air-battery and fly ash research can be encouraged through more inclusive global funding schemes and regulatory standardization of the use of coal industry waste as an electrochemical material.

Judging from the authors who are most prolific researching air batteries and fly ash (Figure 7(c)), it shows the top 10 researchers in air battery research. The top author with 5 air battery publications is written by Purwanto. Aydilek, Bandarra, Jumari, Martins, Pereira, and Quina as the second most authors with the number of publications as many as 4. Meanwhile, Abdel Aziz, Abou El-Khair, and Daoud are ranked third or lowest with 3 air battery publications. Based on the type, the distribution of air battery publications in the world is 55.4% in the type of research articles, 19% in the form of review studies, and the rest in other forms such as conference papers 13.3%, book chapters 2.6%, and so on are shown in Figure 8(a). Judging from the source, the publications that contain the most air batteries are in engineering (20.9%), material science (18%), chemistry (22.1%), environmental science (15.8%), and the rest are shown in Figure 8(b).

Keyword mapping analysis showed results in the form of several main clusters in air battery and fly ash research. However, to ensure that the results reflect a meaningful research structure, the researchers evaluated the characteristics of each cluster according to the frequency of keyword occurrence and their relationship to other topics to identify emerging sub-areas of research. A general visualization of battery publications (Figure 9) shows that many aspects were reviewed by researchers in 2019-2023. If elaborated further, the most battery publications are closely related to fly ash, forming components, waste, battery products, electrodes, and so on. This proves that energy storage in the form of batteries is very important to be developed continuously by looking at its shortcomings, advantages, and potential in the future. If described separately, the trend of fly ash research in 2019-2023, related to the relationship between fly ash and its influence, the compressive strength of fly ash, and the use of fly ash into concrete. In fly ash batteries, it can be used as a source of high-value materials such as silicon (Si) for Li-ion battery anodes as a sustainable solution and more economical waste treatment, as in the publication [61], [62]. In addition, fly ash is also used as the main material of geopolymer cement, silica aerogel, carbon nanotubes, and radioactive isotope separation which is important to reduce the threat of environmental pollution due to the complex toxic content of fly ash waste and to reduce CO2 emissions as in research Gollakota *et al*. [63].

Research examining the use of fly ash in batteries in 2019-2023 has begun to be carried out by researchers around the world. In air batteries, fly ash can be used as a source of high-value materials such as silicon (Si) for Li-ion battery anodes as a sustainable solution and more economical waste treatment, as in the publications in the publication [61], [62]. In addition, fly ash is also used as the main material of geopolymer cement, silica aerogel, carbon nanotubes, and radioactive isotope separation which is important to reduce the threat of environmental pollution due to the complex toxic content of fly ash waste and to reduce CO2 emissions as in research by Gollakota *et al*. [63].

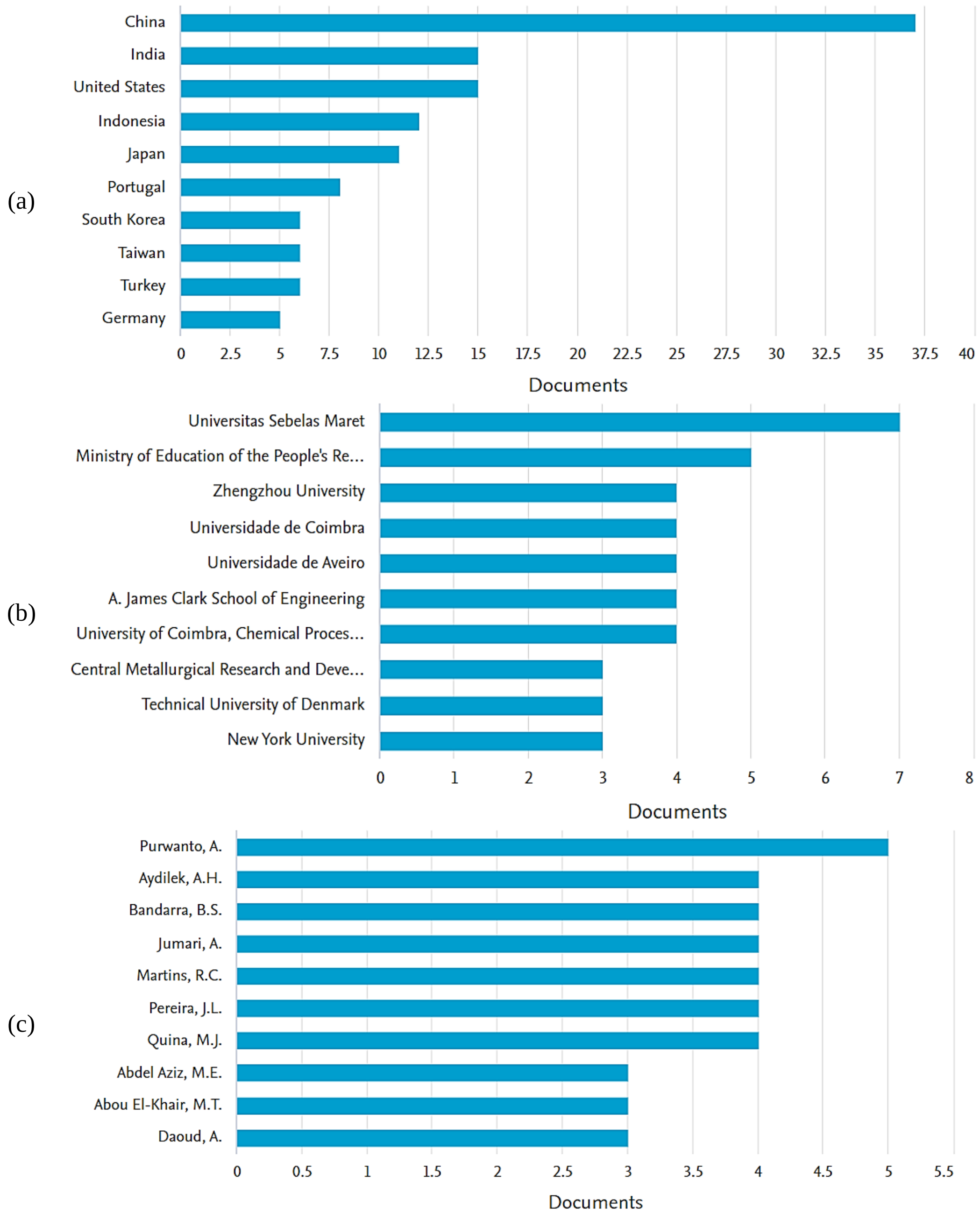

Figure 7. Number of publications "air battery and fly ash" in 2019-2023: (a) between countries, (b) by institutional affiliation, and (c) based on researchers

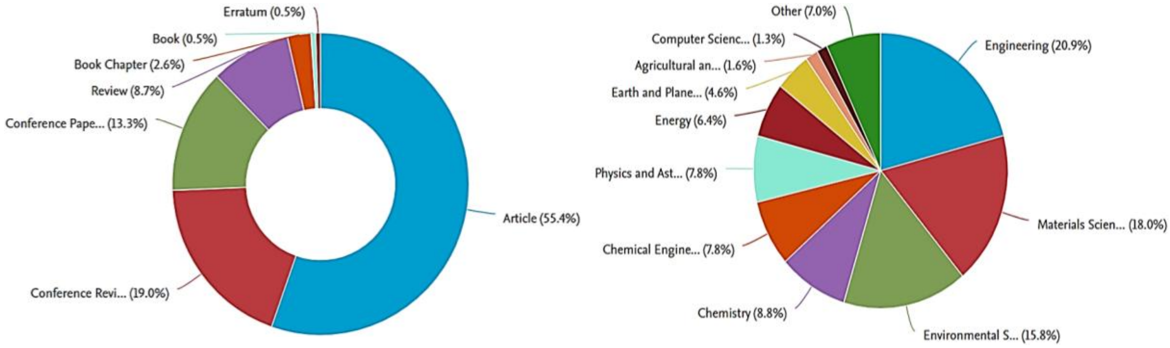

Figure 8. Publication "air batteries and fly ash" by type and source of publication 2019-2023: (a) publication type and (b) publication sources

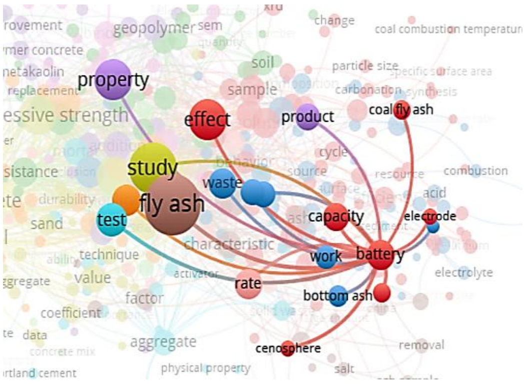

Figure 9. Visualization of air battery publications with fly ash

Based on research [20], trend of lithium-ion battery publications has remained dominant in the last decade, focusing on improving energy density and material safety, while based on research [41] about zinc-air batteries shows a more specific trend in the development of oxygen catalysts and cycle stability. Compared to the two studies, this study shows that publications related to air batteries and fly ash are still in their early stages with relatively slower growth compared to lithium-ion batteries and zinc-air batteries but have a unique focus on the utilization of coal industrial waste as electrode materials. It could have great potential to develop as a sustainable battery alternative. This study is one of the first analyses to specifically map the trend of air battery research with fly ash as an electrode material so that the results can provide new insights into how battery technology is developed by utilizing industrial waste as a more sustainable and environmentally friendly energy solution.

Bibliometric results show that there has been an increase in research related to the use of fly ash as a substitute for carbon in air batteries. But some of the main challenges that must be considered have to do with technical constraints and environmental impacts. Fly ash has a high variation in composition so that its conductivity and stability properties will vary depending on the source. These varied conductivities and stabilities will affect battery performance in the long term, especially on electrochemical efficiency and cycle durability. This is evidenced by previous studies that reveal that although fly ash has high porosity and conductive properties can improve the efficiency of electrodes, surface activation methods, and material doping are needed to improve the performance of air batteries. When viewed from the environmental impact, although the use of fly ash can reduce coal waste, some fly ash contains heavy metals (Pb, Cu, and Zn) that have the potential to pollute the environment if not processed properly. Therefore, further studies are needed to ensure that an effective purification method is applied before it is applied in batteries.

Based on bibliometric visualization (Figure 10), known that the topic of batteries and fly ash has become a trend in battery research today, both from the discussion of anodes in each air battery product, the problems faced, performance, elements, to their capacity and recycling. So, the proposal to manage fly ash waste as a substitute for carbon in air batteries has been studied in advance in the form of proceedings, research articles, investigations, analysis, and so on. However, further development and testing with parameters are still needed to maximize the results. When viewed in terms of conductivity, Fly ash presents a significant opportunity to replace carbon. In addition, fly ash waste is also available in large quantities, so it can be one of the advantages of this waste compared to other materials as a substitute for carbon. Each recycling technology has a different purpose for a specific end product, which makes it difficult. This is because each recycling solution has its own drawbacks and advantages. Battery technology uses active cathode materials that change rapidly, so recycling approaches must change as batteries advance. Instead, the resilience technology must be able to withstand changes in the cathode chemistry [63].

The results of the keyword mapping show that some of the new trends in air battery research are the use of alternative materials other than fly ash (e.g., biochar and other industrial waste). This shows that there has been a shift in focus from fly ash recycling to broader electrochemical material innovation. The analysis also revealed that there has been an increase in research related to cycle stability and electrode performance optimization strategies, which can be the direction of future research development. This study identifies a shift trend from material exploration to improved efficiency and industrial applications, so that it can be affirmed that the research is not only focused on the characterization of materials but also the implementation of fly ash-based battery technology in the context of renewable energy.

The keyword visualization shows that fly ash research in air batteries is developing in several directions, one of which is focusing on material characterization and electrode optimization as well as more discussion related to sustainability and environmental impact so that to overcome technical and environmental challenges collaboration between disciplines is needed. Research on fly ash in air batteries covers several key disciplines, namely engineering, materials science, and environmental science. Engineering studies focus on the production and design of fly ash-based electrodes, materials science focuses on research on the microbial structure and electrochemical properties of fly ash as a substitute for carbon in air batteries, while environmental science focuses on the study of the potential impact of the use of fly ash and purification techniques before being used as electrode materials. Future research can collaborate environmental purification engineering approaches with artificial intelligence-based material simulations and electrochemical optimization using nanotechnology. The collaboration created between disciplines is expected to encourage the acceleration of fly ash-based battery innovation that is more efficient and sustainable.

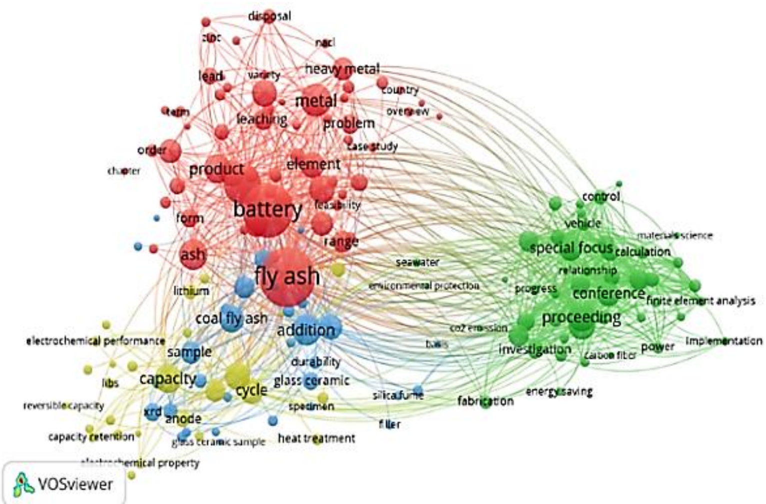

Figure 10. Keyword co-occurrence mapping: air batteries and fly ash (2019-2023)

4. CONCLUSION

High-energy density air batteries are being developed to support sustainability and decarbonization, but they still use less environmentally friendly carbon anodes. Research is moving towards the use of fly ash as an alternative to carbon. Bibliometric analysis (2019-2023) shows that China dominates air battery research with more than 5,500 publications, while fly ash-related research is led by China (37 publications), followed by India and the US (15), and Indonesia (12). Sebelas Maret University is the most productive institution, with Purwanto as one of the lead authors. The study highlights the potential of fly ash for battery anodes and other applications, although further research is needed to optimize its use and overcome technical challenges.

Research on metal-air batteries and the use of fly ash as a carbon substitute in this context highlights some significant implications. The use of fly ash, waste from the coal industry, as an anode material in metal-air batteries offers a more environmentally friendly solution with the potential to reduce the negative impact of industrial waste. Not only does it support the concept of a circular economy by utilizing waste as a valuable resource, but it can also reduce reliance on more polluting carbon materials. In addition, this research also shows the development of more sustainable battery technology with the potential to improve the performance and efficiency of metal-air batteries. The bibliometric analyses conducted not only identify research trends and key focuses in this domain but also reveal collaborative networks between researchers and institutions, facilitating the exchange of ideas and cross-disciplinary research. Further implications of the study include its potential impact on energy policy and investment, encouraging governments and industry to support the development of innovative and sustainable eco-friendly battery technologies.

This research is in line with the global agenda related to decarbonization and the circular economy. The utilization of fly ash coal waste will help reduce dependence on conventional carbon resources. In the context of clean energy policy, the use of fly ash can be included in the "Green Industry Initiative" program to improve the efficiency of raw materials and reduce coal waste. Fly ash-based air battery research can play an important role in supporting sustainable energy policies in countries such as China, the European Union, and the United States that have implemented strict policies related to the reduction of industrial carbon emissions, including regulations that encourage innovation in energy storage based on recycled materials.

In order for fly ash-based air battery research to develop faster towards commercialization applications, several important stages are needed, starting from the stage of material optimization and fly ash purification to remove toxic heavy metals without reducing their conductivity, understanding their structure, electrode properties, and performance compared to conventional carbon. After that, electrochemical testing and prototype development were carried out using cyclic voltammetry (CV) and galvanostatic charge-discharge (GCD), and evaluation of battery performance under various conditions (e.g., at extreme temperatures and high humidity). Then it can collaborate with the battery industry and manufacturing to carry out large-scale trials as well as develop life cycle assessment (LCA), efficiency, and battery life. In order for fly ash-based air battery technology to develop faster and widely, the government can provide intensive services to universities or companies that conduct fly ash research in batteries. In addition, international collaboration for the standardization of fly ash-based energy storage technology can also be carried out so that the technology can be implemented globally without different regulatory barriers in each country.

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C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

INFORMED CONSENT

We have obtained informed consent from all individuals included in this study.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author, [SP], upon reasonable request.

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