Journal of Scientometric Research, 2024; 13(3):757-772.
https://www.jscires.org

Research Article

Recycled Concrete Aggregates Utilization in Construction: Publications Trends, Bibliometric Analysis, and Literature Review, 2011-2021

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ABSTRACT

Recycled Concrete Aggregates (RCA) are the product of recycling Concrete and Demolition Wastes (CDWs) from the construction industry. The practice aims to effectively dispose of, manage, and treat solid wastes that could pose health, safety, and environmental concerns. To address these impending problems, CDWs are valorized into RCA as a substitute for Natural Aggregates (NA) during construction. Hence, various studies have been published on the use of RCA as a partial replacement for NA in concrete as well as the properties of RCA-based concrete mixes. This study employs scientometric analysis to quantitatively assess the scientific literature on Recycled Concrete Aggregates (RCA). The Systematic Literature Review (SLR) of Recycled Concrete Aggregates (RCA) utilization in construction was critically examined using the PRISMA approach. VOSviewer was utilized for the bibliometric analysis to map co-authorship networks, keyword occurrence, and co-citation analysis. The bibliometric analysis reveals a substantial increase in publications on RCA utilization over the 10 years, demonstrating growing interest and awareness in sustainable construction practices, which translates to significant contributions in areas such as performance enhancement, material properties, and environmental sustainability. The SLR indicated that the partial replacement of fine or coarse NA with RCA in concrete improves the physical durability, workability, and mechanical properties. It also reduces the industry's overall carbon footprint and addresses environmental issues related to construction. Thus, the study contributes to the understanding of RCA utilization in the construction industry and provides valuable insights for researchers, practitioners, and policymakers seeking to promote sustainability in the built environment. Future studies could look at novel composite materials, the effects of RCA production on the environment, and the long-term effectiveness of RCA in building applications.

Keywords: Recycled Concrete Aggregates (RCA), Construction and Demolition Wastes (CDWs), Sustainable Construction Practices, Bibliometric Analysis, Environmental Sustainability, Circular Economy in Construction.

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Received: 14-05-2024;
Revised: 05-06-2024;
Accepted: 27-07-2024.

INTRODUCTION

The socio-economic growth and infrastructural development of global nations are strongly influenced by the construction industry.[1,2] The sector provides critical social infrastructure such as homes, hospitals, schools, roads, water, transportation, and sanitation, as well as improved standards of living through job creation, social safety nets, and a peaceful environment for people to thrive.[3,4] Despite its immense contribution to human existence, the construction industry is a significant contributor to the environmental burden caused by various streams of solid and fluid-based wastes.[5,6] One of the most common solid wastes generated during the Construction, Demolition, and Renovation Wastes (CDRW) is also known as Construction and Demolition Wastes (CDW).[7-9]

The CDW generally consists of four-fifths of excavated soils and stone, along with waste plastics, bricks, concrete, metals, tiles, glass, and wooden debris.[9-11] According to El Haggar,[10] CDW is a heterogeneous mixture of building materials comprising wood, aggregate, paper, metal, concrete, insulations, and glass but also other constituents such as adhesives, fasteners, paints, insulation, dirt, and wall coverings. The CDW is typically generated from structural development, engineering works, and demolition or tearing down processes of existing structures during renovations, remodeling, and or construction works.[9] In addition, CDWs

DOI: 10.5530/jscires.20041311

are generated from natural catastrophic events including but not limited to hurricanes, floods, tsunamis, or earthquakes, among others.[10]

Typically, the constituents and quantity of CDW generated are a function of various factors, including the building structure typology, selected building materials, and structure lifespan.[10] For example, it is estimated that the quantity of CDWs generated overall is between 1.0 ton/m^2 to 2.0 ton/m^2 of the total area of the ground level. Specific estimates for the CDWs generated from domestic buildings range between 1.3 ton/m^2 and 1.6 ton/m^2 of the structural area of the ground floor, whereas, for industrial structures, it is between 1.5 ton/m^2 to 2.0 ton/m^2 of the entire area under demolishing.[10,12] The data shows that large quantities of CDWs are generated from the industry annually, which could pose grave risks to human health, occupational safety, and environmental stability. Against this backdrop, analysts estimate that the construction industry is reportedly responsible for 8% of the total GHG emissions and about 40% of energy-related emissions of Greenhouse Gases (GHG) released annually into the planet.[13,14]

With the growing demand for critical social infrastructure and building structures around the world, it is projected that volumes of solid waste streams and GHG emissions generated by the construction industry will soar exponentially in the coming years if no action is taken. The short- and long-term challenges posed by waste streams from the construction industry require urgent global attention. Given this, the COP21 (conference of parties) or the Paris Agreement was ratified in the year 2015 by signatory nations who pledged to drastically cut down Greenhouse Gas (GHG) emissions from 50 billion tonnes from various sectors to limit global warming to 1.5°C by the year 2050.[15,16] Therefore, the proper disposal and effective management of these streams could reduce GHG emissions and pollutant materials and safeguard human health and the environment. Alternatively, many researchers have examined the valorization of CDWs into alternative building materials and construction inputs for the construction industry.[17-19]

One of the most notable products from the valorization of CDW is Recycled Aggregates (RA). Recently, the process of recycling has been championed as a practical approach to address the problems of various forms of solid waste such as CDWs in the industry. Hence, the high concrete compositions of most CDW streams present opportunities for the production of valuable products such as recycled concrete aggregates, or RCA for short. In theory, RCA is aggregates produced by recycling concrete wastes either onsite, stationary/mobile recycling, or processing facilities.[20] According to the British standard BS 8500-2 BSI 2006, RCA is described as RA comprising 5% maximum masonry/fines, 0.5% maximum lightweight material/asphalt, and 1% maximum other foreign materials.[21]

The production of RCA involves the two-stage process of crushing and then the removal of contaminants (e.g., dirt, plaster, gypsum, and other building wastes) before screening.[20] According to Purnell and Dunster,[22] RCA is also produced by crushing reinforced as well as plain (non-reinforced) concrete, which indicates that it consists of graded inorganic particles. Typically, the RCA is processed into similar coarse aggregate sizes to natural crushed rock aggregates. Hence, the surface texture of RCA particles appears to be slightly rougher than natural aggregates owing to the adhering cement mortar.[22] The production and extended use of RCA present numerous opportunities. For example, RCA lowers the environmental burden of CDWs as well as its associated challenges.[20] Furthermore, RCA is considered a reliable alternative that could help preserve natural aggregate resources when used during construction.[23]

However, RCA has some drawbacks, such as the presence of extraneous materials such as glass, metals, plastic, and wood particles, among others, and high quantities of masonry.[22] Furthermore, RCA is highly hydrophilic, which results in increased water absorption due to the high porosity of the observed mortar.[24-27] According to Katz[28] and Martín-Morales *et al.*,[29] the water absorption capacity of RCA is 3-12% higher than the fine and coarse portions of NA. Hence, RCA-based concretes are prone to mechanical and durability issues,[30] as well as physical properties and workability.[22] Recently, Dhir *et al.*,[31] reported that the addition of RCA to concrete increases the water absorption capacity at rates directly proportional to the additive content. Given these challenges, the utilization of RCA in many countries is either restricted or prohibited for health, safety, and environmental reasons. For example, the replacement of RCA is restricted to 20% in structures in countries such as the Netherlands, Britain, and Spain.[23]

Over the years, numerous studies have been carried out to further examine the potential of RCA and to address the challenges associated with its utilization in the construction industry. Other studies have also examined the potential human health, occupational health, and environmental impacts of RCA production, utilization, and end life. The Elsevier Scopus data shows that 2,131 documents have been published from 1977 to date based on the TITLE-ABS-KEY search criteria of the keywords search query ("recycled concrete aggregate*"). However, this large data set of materials cannot be effectively analyzed to examine the research growth and technological developments in the subject area. Therefore, this study has adopted the results TITLE search criteria to examine the research landscape and scientific developments on Recycled Concrete Aggregates (RCA) utilization in the scientific literature. It is envisaged that the findings will avail newcomers and established researchers with comprehensive developments on the subject area.

Several tools and techniques have been proposed to methodically identify, filter, and evaluate the state of research and scientific

advancements in many fields. The Bibliometric Analysis Technique (BAT) is one of the most often utilized methods. Thus, the study uses bibliometric analysis to evaluate the scientific literature on Recycled Concrete Aggregates (RCA) spanning between 2001 and 2021 from published documents retrieved from the Elsevier Scopus database. Bibliometric analysis is a scientific method employed to quantitatively evaluate the impact and dissemination of research within a particular field. It also entails the statistical analysis of articles, citations, and other metrics to map the networks of collaboration between researchers and institutions, assess the impact of research publications, and identify new research trends. This approach is especially helpful for understanding how scientific fields have evolved, changed, and affected society over time.

METHODOLOGY

The publications trends, bibliometric analysis, and systematic literature review of Recycled Concrete Aggregates (RCA) utilization in construction were examined in this study using the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) technique. It involves a four-phase flow diagram for identification, screening, eligibility, and inclusion to ensure a comprehensive and unbiased selection of relevant literature. The detailed procedures of the PRISMA technique are adequately described in the scientific literature.[32-35] To improve the reliability and transparency of systematic reviews, PRISMA techniques are used.to identify, screen, and analyze all the related literature on RCA utilization published and indexed in the Elsevier Scopus database as shown in Figure 1. The Scopus database is selected for

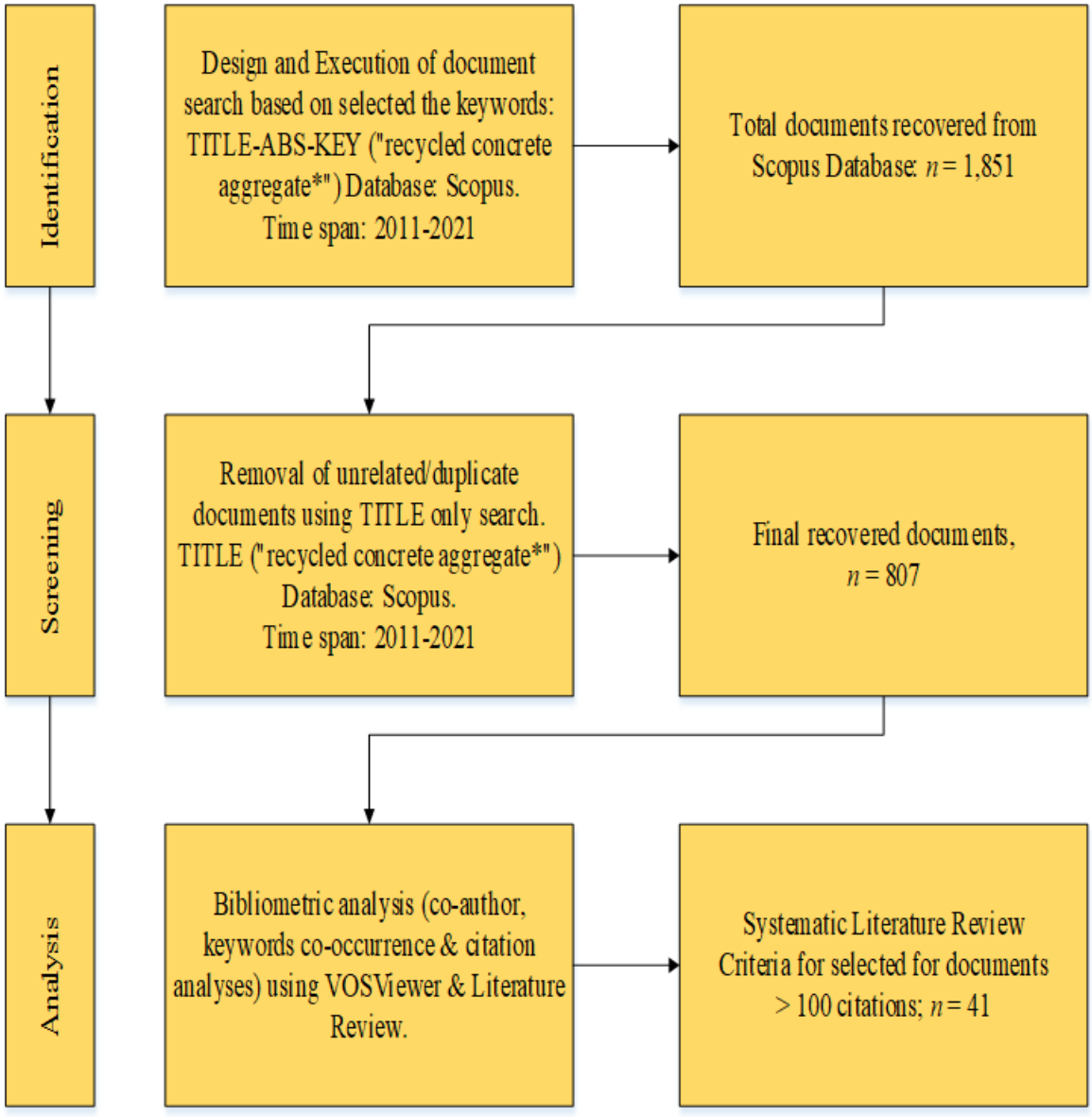

Figure 1: PRISMA methodology for published documents recovery on RCA (2011-2021).

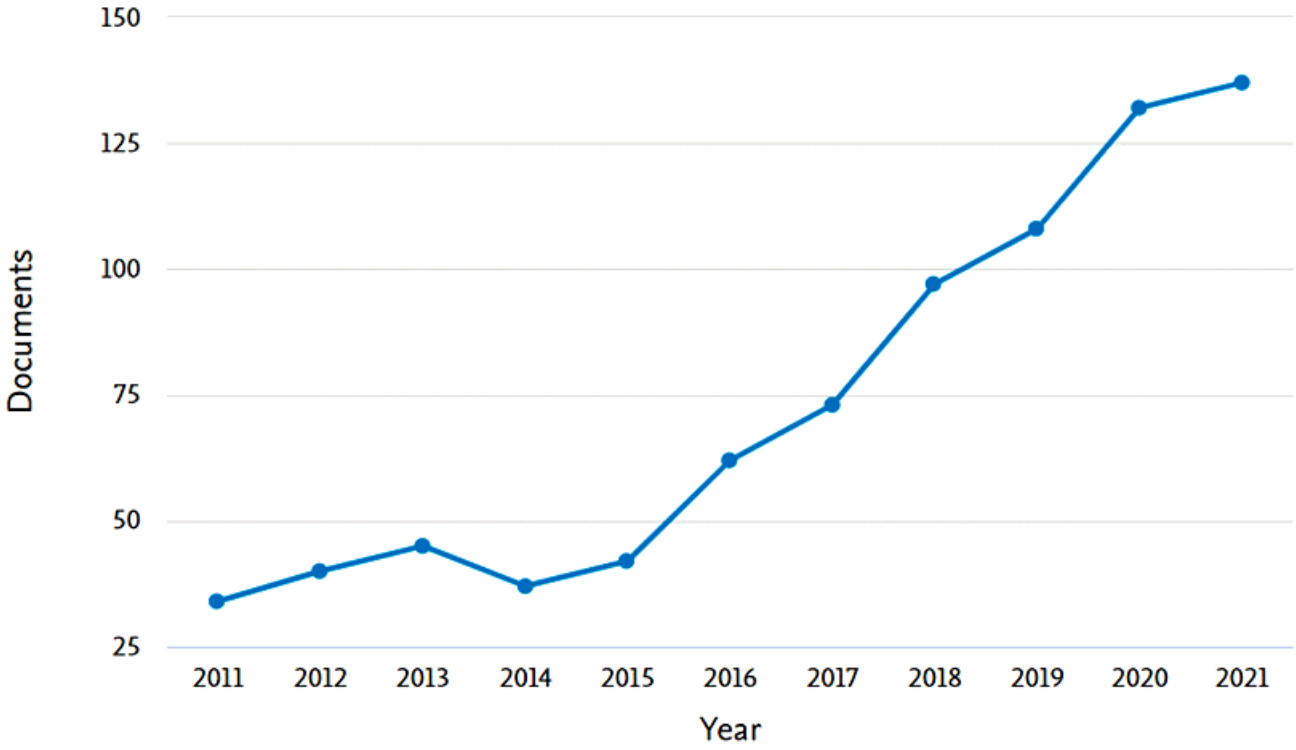

Figure 2: Publication trends analysis on RCA Utilization (2011-2021).

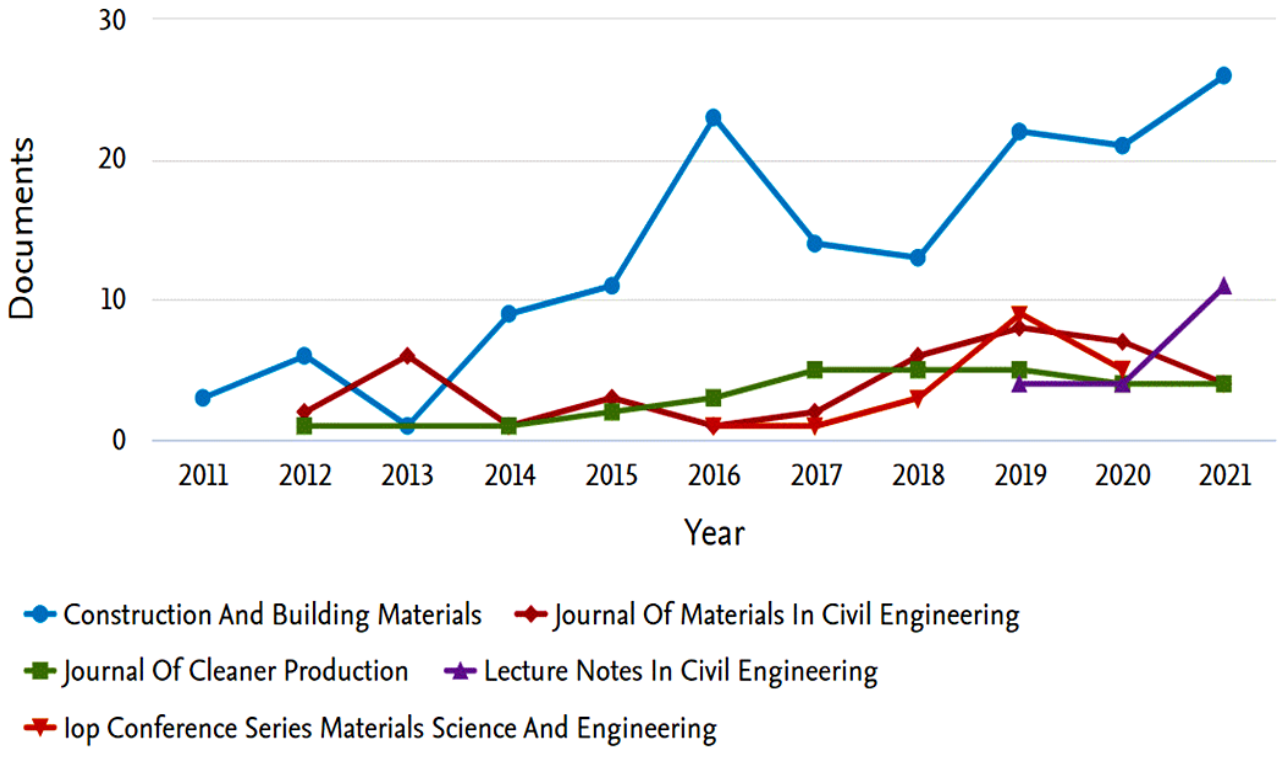

Figure 3: Source titles for articles published on RCA Utilization (2011-2021).

the study due to the vast coverage of high-quality peer-reviewed literature in the fields of science, medicine, technology and social sciences ensuring the reliability of the data. Scopus's extensive indexing of journals, conference proceedings, and academic sources ensures a broad view of the research landscape. In addition, Scopus provides detailed citation data, facilitating thorough bibliometric analysis, and sophisticated search tools and filters for effective retrieval of relevant articles. These characteristics make Scopus a good option for carrying out an exhaustive and precise scientometric examination.

Firstly, the published documents on RCA utilization were identified by designing an appropriate search string based on the title keywords, "recycled concrete aggregates"). Consequently, the search query ((TITLE ("recycled concrete aggregate*") AND PUBYEAR > 2010 AND PUBYEAR < 2022)) was executed in the Scopus database to recover related documents on the subject theme in the literature. Next, the documents were screened to filter any unrelated documents in the dataset before the final analysis. The recovered documents were subsequently analyzed to examine the publication trends, significant stakeholders, and top-cited documents on RCA utilization. The co-authorship network was mapped using VOSviewer to identify collaborations between researchers and academic institutions. The VOSviewer assisted in visualising the keyword co-occurrence network revealing major research topics and trends. Furthermore, co-citation network analysis was made possible by VOSviewer which shows the most frequently cited publications and their relationships

Lastly, the research growth and scientific developments on the subject area were examined through a Systematic Literature Review (SLR) of the topmost cited or benchmark papers on RCA utilization. The criteria for screening and final selection for SLR were based on documents with 100 or more citations, which is considered the topmost and sufficient for critical analysis.[36]

RESULTS AND DISCUSSION

Publication Trend Analysis

Figure 2 shows the growth trends in published documents on the utilization of RCA in the construction industry over the years from 2011 to 2021. The findings show that 807 documents have been published in the subject area during the 10 years examined in this study. As observed in Figure 2, the publication trends of RCA-related research from 2011 to 2023 increased from 34 in 2011 to 137 in 2021. This trend indicates growing interest and awareness in the field of sustainable construction practices. The surge (302.94%) in publications can be attributed to increased environmental concerns and the need for sustainable waste management solutions in the construction industry.

Table 1: Document types for RCA publications (2011-2021).

Document Type	Total Publications (TP)	Percentage of Total Publications (%TP)
Article	581	72.00
Conference Paper	175	21.69
Review	28	3.47
Book Chapter	18	2.23
Note	3	0.37
Erratum	1	0.12
Short Survey	1	0.12

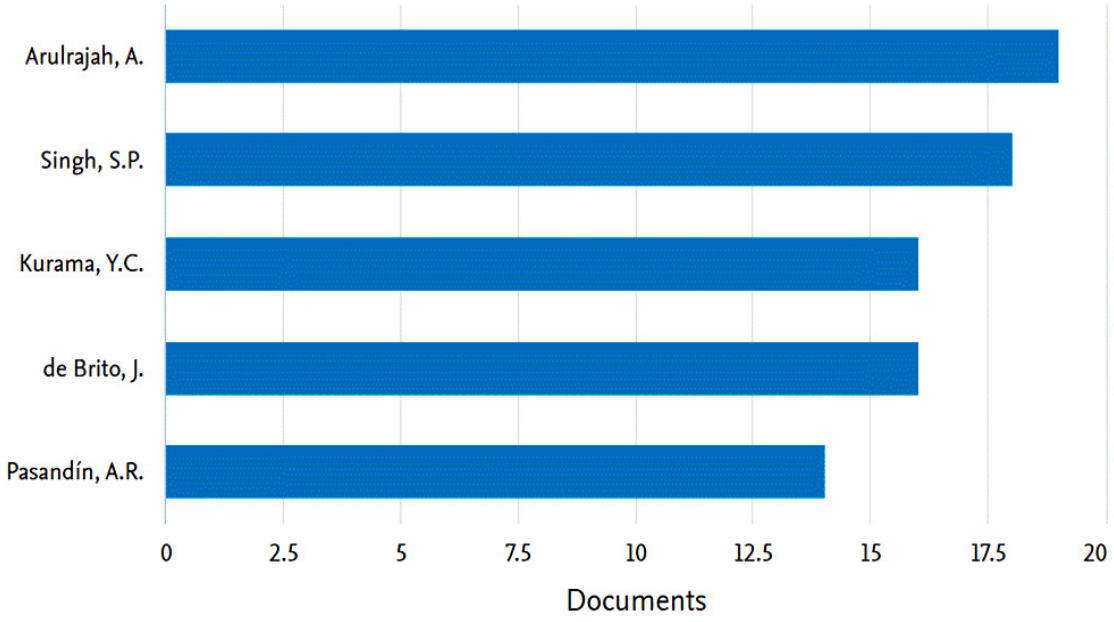

Figure 4: Top 5 most prolific authors on RCA Utilization (2011-2021).

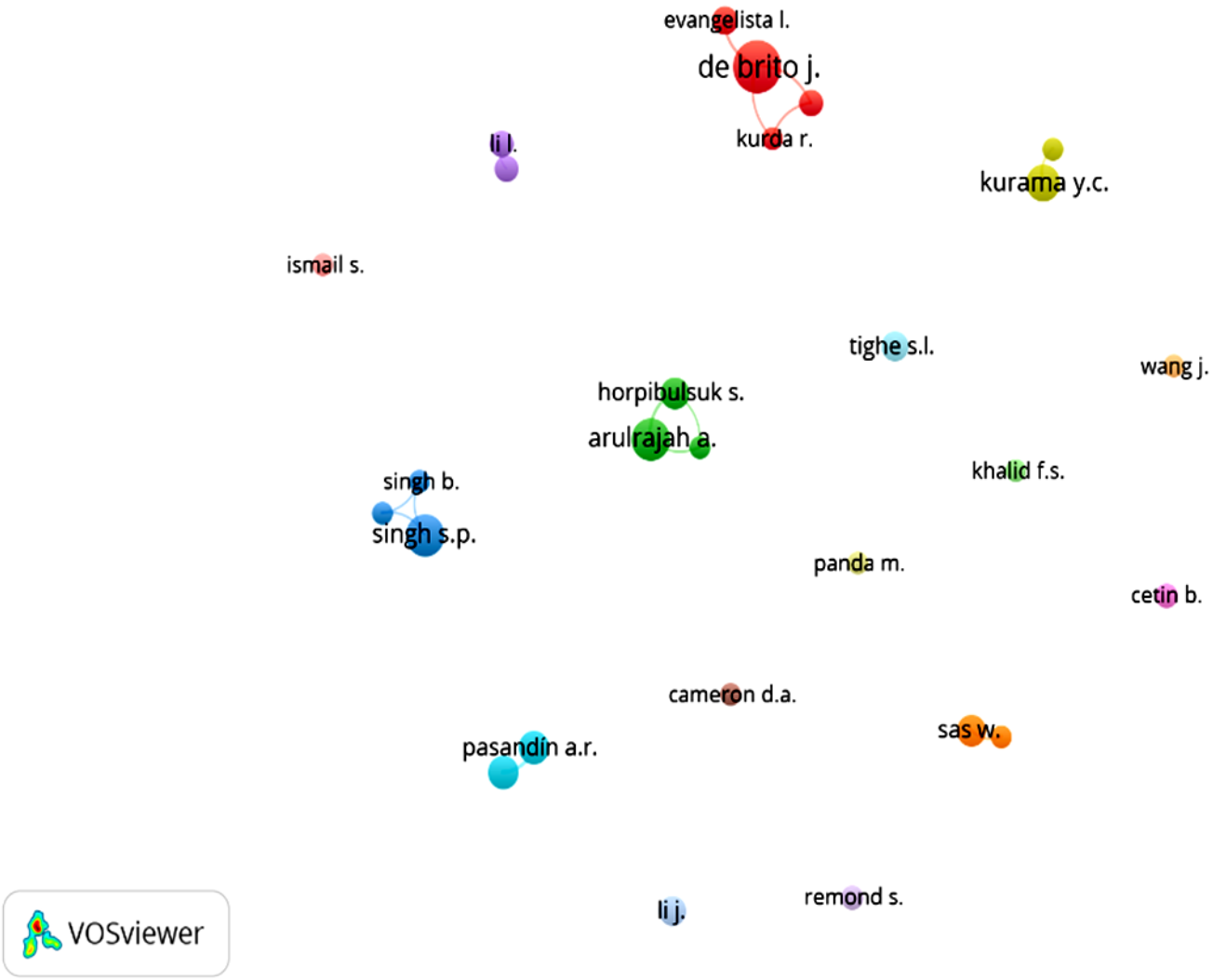

Figure 5: Network visualization map for co-authorship among RCA researchers.

Further observation shows that despite the geometric increase in publications over the 10-year period, the number of publications remained below 50 in the first five years of the study from 2011 to 2015. However, an upward trend was observed after 2015, which may be due to several factors. The increase in published documents from 42 in 2015 to 62 in 2016 could be to some extent ascribed to the global calls for sustainable practices in the construction industry. According to analysis, the use of cement in the construction industry accounts for 8% (4 billion tonnes) of the total GHG emissions released annually onto the planet.[37] In a separate study, the UNEP reports that the construction industry ~40% of all energy-based GHG emissions are due to activities in the buildings and construction industry.[37] With the ratification of the COP21 (conference of parties) Paris Agreement in the year 2015, signatory nations pledged to drastically cut down Greenhouse Gas (GHG) emissions from 50 billion tonnes to limit global warming to 1.5 °C by the year 2050.[15,16]

Hence, it can be reasonably surmised that one of humanity's potential chances of slowing global warming and climate change is to ring in significant changes in the building and construction sectors of the world's economy. One such opportunity is the transition from a linear economy to a low carbon circulation based on the solid wastes' valorization and sustainable utilization of materials (such as recycled concrete aggregates, which is the crux of this study). Over the years, numerous researchers have identified and examined various techniques and materials in the construction industry, resulting in numerous publications of various types and subject themes. Table 1 shows the various document types for the various published documents on the subject area from 2011 to 2021 recovered from the Scopus database. The findings show that the published documents on RCA from 2011 to 2021 have been published in various formats from articles to short surveys. The preferred format for publication is articles with 581 documents or 72% of the total publications on the subject area. Other notable formats are conference papers and reviews which account for 21.69% and 3.47% of the total

Table 2: Key details of source titles on RCA (2011-2021).

Source Title	TP	%TP	Source Type	CS	SJR	SNIP
Construction and Building Materials	149	18.46	Journal	8.800	1.662	2.483
Journal of Materials in Civil Engineering	40	4.96	Journal	4.700	1.090	1.409
Journal of Cleaner Production	30	3.72	Journal	13.100	1.937	2.475
IOP Conference Series Materials Science and Engineering	19	2.35	Conference Proceeding	0.700	0.198	0.484
Lecture Notes in Civil Engineering	19	2.35	Book Series	0.300	0.108	0.699
Journal of Building Engineering	17	2.11	Journal	5.500	0.974	2.290
Materials	17	2.11	Journal	4.200	0.682	1.261
Cement and Concrete Composites	16	1.98	Journal	10.900	2.896	2.522
Geotechnical Special Publication	15	1.86	Conference Proceeding	0.600	0.258	0.285
Transportation Research Record	15	1.86	Book Series	2.400	0.624	0.869

TP-Total publications; CS-Citescore; %TP-Percentage of total publications; SJR SCImago Journal Rank; SNIP- Source Normalized Impact per Paper.

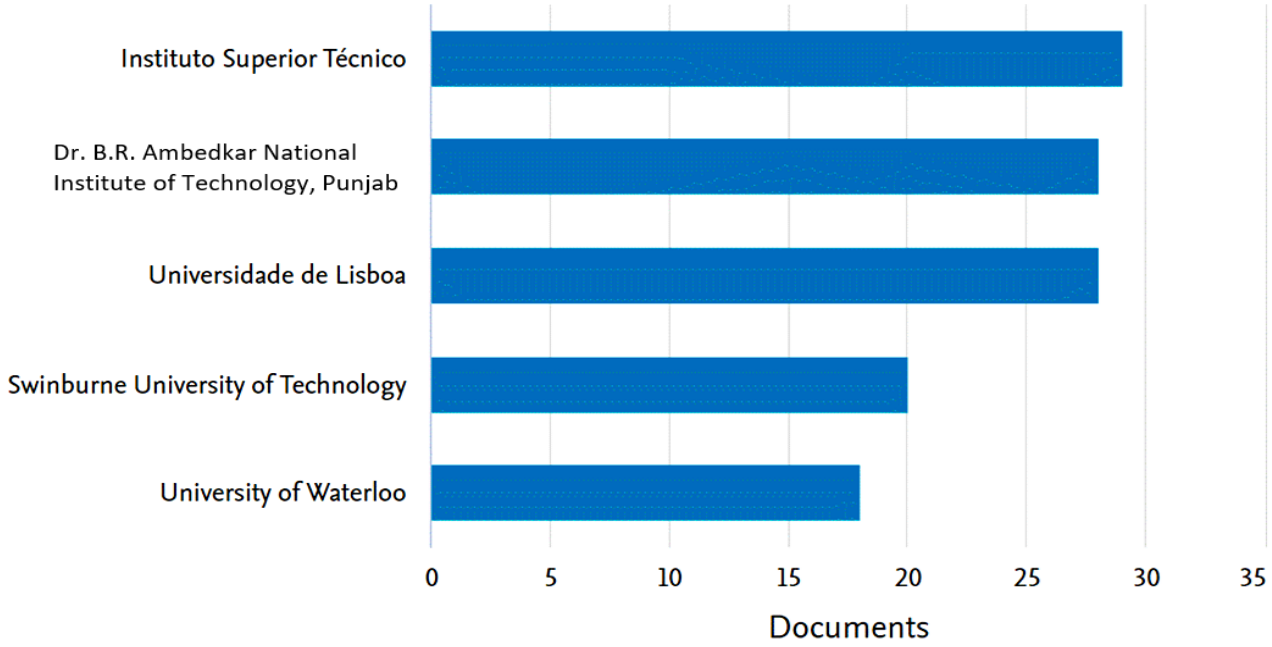

Figure 6: Top 5 most active research affiliations on RCA Utilization (2011-2021).

publications. However, the least common formats are notes, errata, and short surveys.

The high number of published articles indicates that the subject area is well established, and hence researchers opt for the traditional peer-review journals to disseminate their findings on the subject. Furthermore, the prestige, incentives, and awards associated with the publication of scientific findings in high-impact peer-reviewed journals is another notable factor that determines the preference of articles when compared to other publication formats in scientific publishing. Therefore, the topmost prestigious source titles for publications on RCA were examined as shown in Figure 3, whereas the journal key details are summarised in Table 2.

The data revealed that the top 10 source titles on RCA utilization had published 337 publications, which account for 41.76% of the total publications on the subject area. Furthermore, the analysis showed 60% of the top 10 sources are journals, whereas 20% are book series and conference proceedings each. Further analysis shows that each journal source has each published 15 or more papers or 33.7 on average over the period examined in the study. The top three journals' sources are; Construction and Building Materials (CBM), Journal of Materials in Civil Engineering, and Journal of Cleaner Production (JCP) with 149 (or 18.46%TP), 40 (or 4.96%TP), and 30 (or 3.72%TP), respectively.

Table 2 also shows the Citescore (CS), SCImago Journal Rank (SJR), and Source Normalized Impact per Paper (SNIP) for the source titles. The CS is defined as the average citations gained by each document published by the source title, whereas the SJR is an indication of the total citations gained by a source title. Lastly, the SNIP is an indication of the definite citations gained by a source

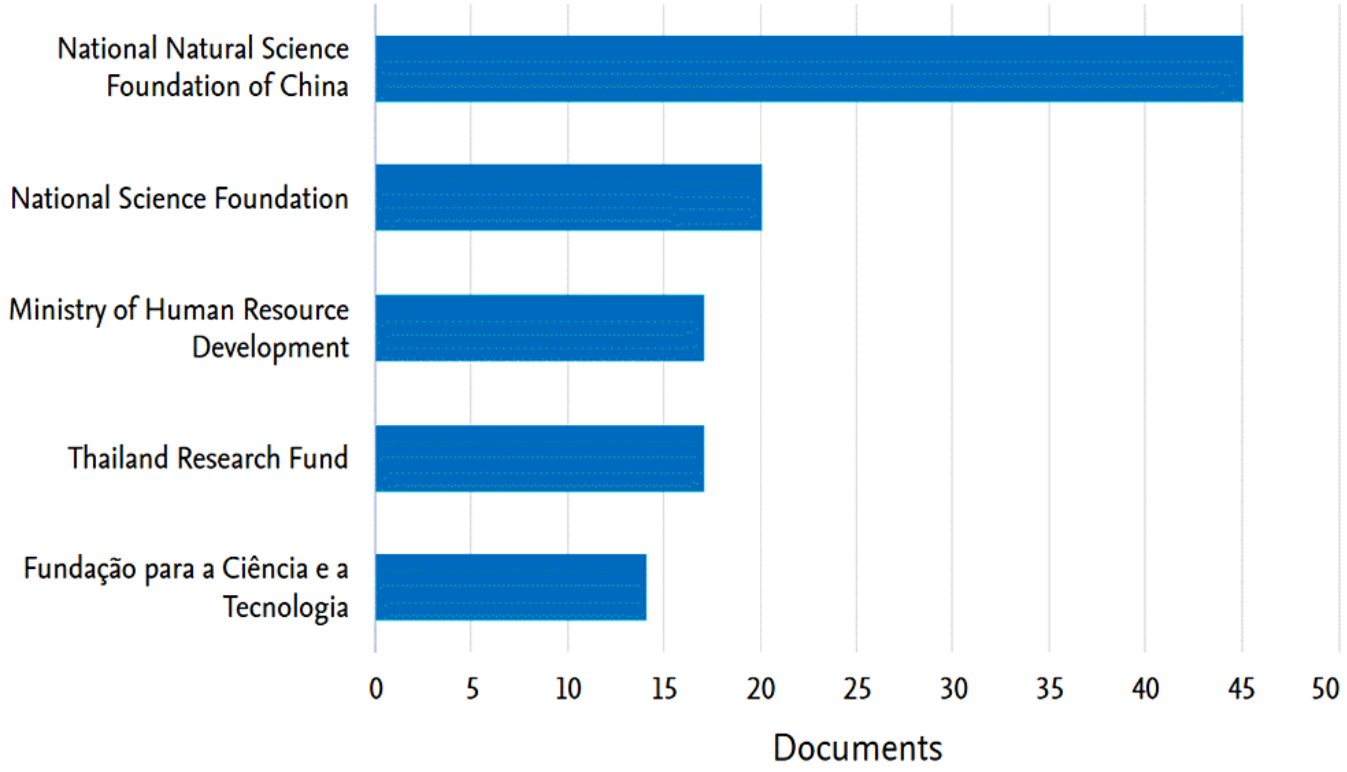

Figure 7: Top 5 funding organizations on RCA Utilization (2011-2021).

Table 3: Top 10 most cited publications on RCA Utilization (2011-2021).

References	Title	Source title	Cited by
Shi *et al.*,[44]	"Performance enhancement of recycled concrete aggregate - A review"	"Journal of Cleaner Production"	412
Limbachiya *et al.*,[45]	"Use of recycled concrete aggregate in fly-ash concrete"	"Construction and Building Materials"	289
McNeil and Kang[46]	"Recycled Concrete Aggregates: A Review"	"International Journal of Concrete Structures and Materials"	242
Butler *et al.*,[47]	"The effect of recycled concrete aggregate properties on the bond strength between RCA concrete and steel reinforcement"	"Cement and Concrete Research"	234
Yang *et al.*,[48]	"Concrete with recycled concrete aggregate and crushed clay bricks"	"Construction and Building Materials"	234
Akbarnezhad *et al.*,[49]	"Microwave-assisted beneficiation of recycled concrete aggregates"	Construction and Building Materials	215
Verian *et al.*,[50]	"Properties of recycled concrete aggregate and their influence in new concrete production"	"Resources, Conservation and Recycling"	208
Xuan *et al.*,[51]	"Assessment of mechanical properties of concrete incorporating carbonated recycled concrete aggregates"	"Cement and Concrete Composites"	206
Ismail and Ramli[52]	"Engineering properties of treated Recycled Concrete Aggregate (RCA) for structural applications"	"Construction and Building Materials"	185
Pereira *et al.*,[53]	"The effect of superplasticizers on the workability and compressive strength of concrete made with fine recycled concrete aggregates"	"Construction and Building Materials"	185

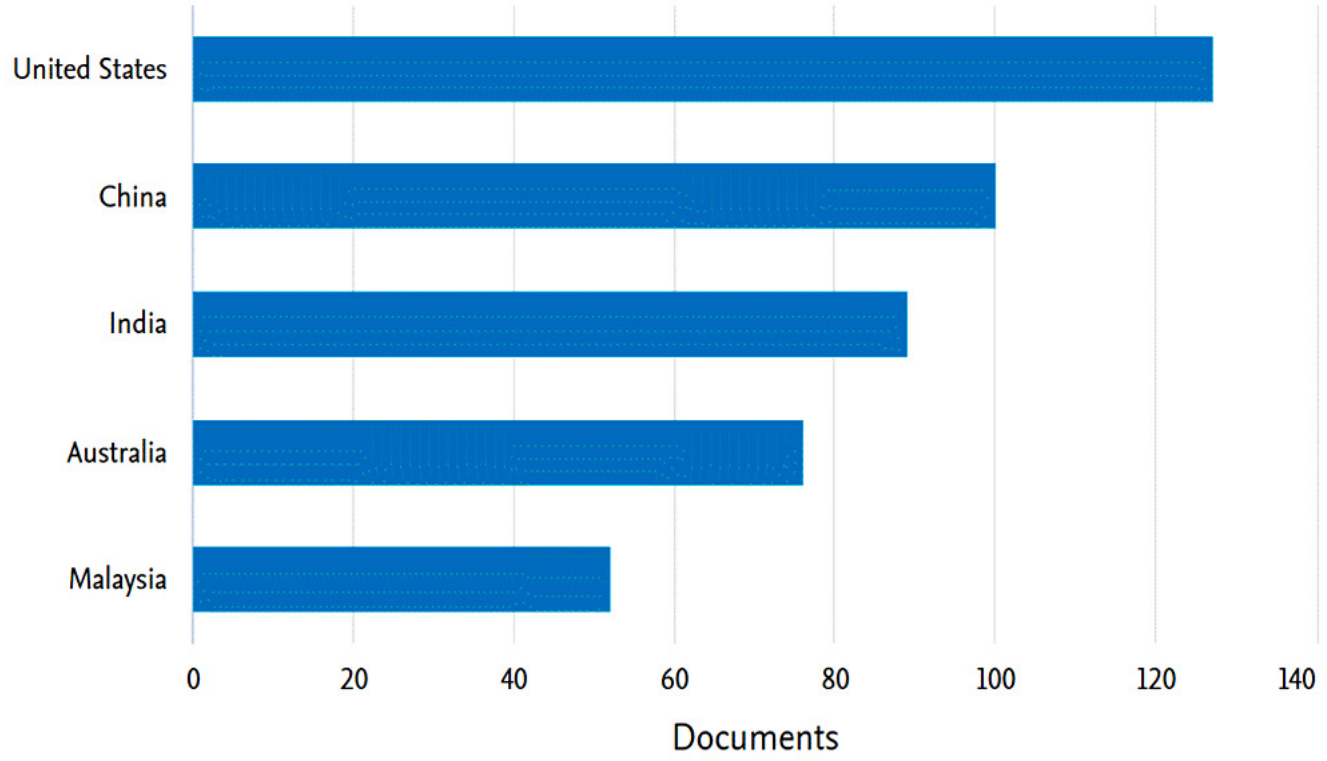

Figure 8: Top 5 most active countries researching RCA Utilization (2011-2021).

title compared to the expected citations in its subject field. As observed in Table 2, the CS, SJR, and SNIP for the top 10 source titles on RCA utilization range from 0.3-13.1, 0.108-2.896, and 0.285-2.522, respectively. The average values of the CS, SJR, and SNIP are; 5.12, 1.043, and 1.478, respectively. The source titles with the highest CS values are; Journal of Cleaner Production (13.1), Cement and Concrete Composites (CCC) (10.9), and Construction and Building Materials (8.8), which indicate that these journals are the most cited, references, and high impact journals on the subject. Based on SJR, the top journals are in the order CCC > JCP > CBM, whereas the order of top journals based on SNIP is CCC > CBM > JCP.

The critical analysis of the CS, SJR, and SNIP data shows that the most prominent journal on RCA utilization is Cement and Concrete Composites (CCC). The journal's website states that CCC is "designed to reflect current developments and advances in cement-concrete composites technology and the production, use, and performance of cement-based construction materials." Studies on "novel aspects of conventional concrete materials and composite materials, such as fiber-reinforced cement composites, polymer cement composites, polymer impregnated composites, ferrocement, and cement composites containing special aggregate inclusions or waste materials" are sometimes published in the journal. Hence, the published documents on RCA are within the scope of CCC, which confirms the journal is the most suitable for publishing studies in the area. The second most crucial journal CBM is also known to publish novel findings on the investigation of innovative building materials for application in maintenance, repair, and new construction works. The prestigious nature of the journals has prompted the patronage of top academics and researchers in the field, as will be examined in section II of the paper.

Major Research Stakeholders

The critical analysis of the top researchers, affiliations, funding bodies, and countries actively researching topics in any field of study can present insights into the research landscape and scientific impact of the area.[38,39] The top 5 most active researchers on RCA utilization in construction are shown in Figure 4, whereas the most productive research affiliations are illustrated in Figure 6.

As observed, the top 5 researchers have each published 12 or more publications over the time frame examined in this study. Based on the total number of publications, the most productive researcher on RCA research is Arul Arulrajah with 19 published papers. The most prolific researcher is closely followed by Surinder P. Singh and Yahya C. Kurama with 18 and 16 published documents, respectively. Other researchers with notable contributions include Jorge De Brito (16) and A.R. Pasandín (14). Overall, the output of the top 5 researchers accounts for 83 publications or 10.29% of the TP on the subject area. The high productivity of researchers is often ascribed to factors such as (but not limited to) access to collaborations, institutional/national policies, and research funding among others. The effect of collaborations (co-authorships) on the productivity of the top researchers on RCA was examined through co-authorship analysis using the

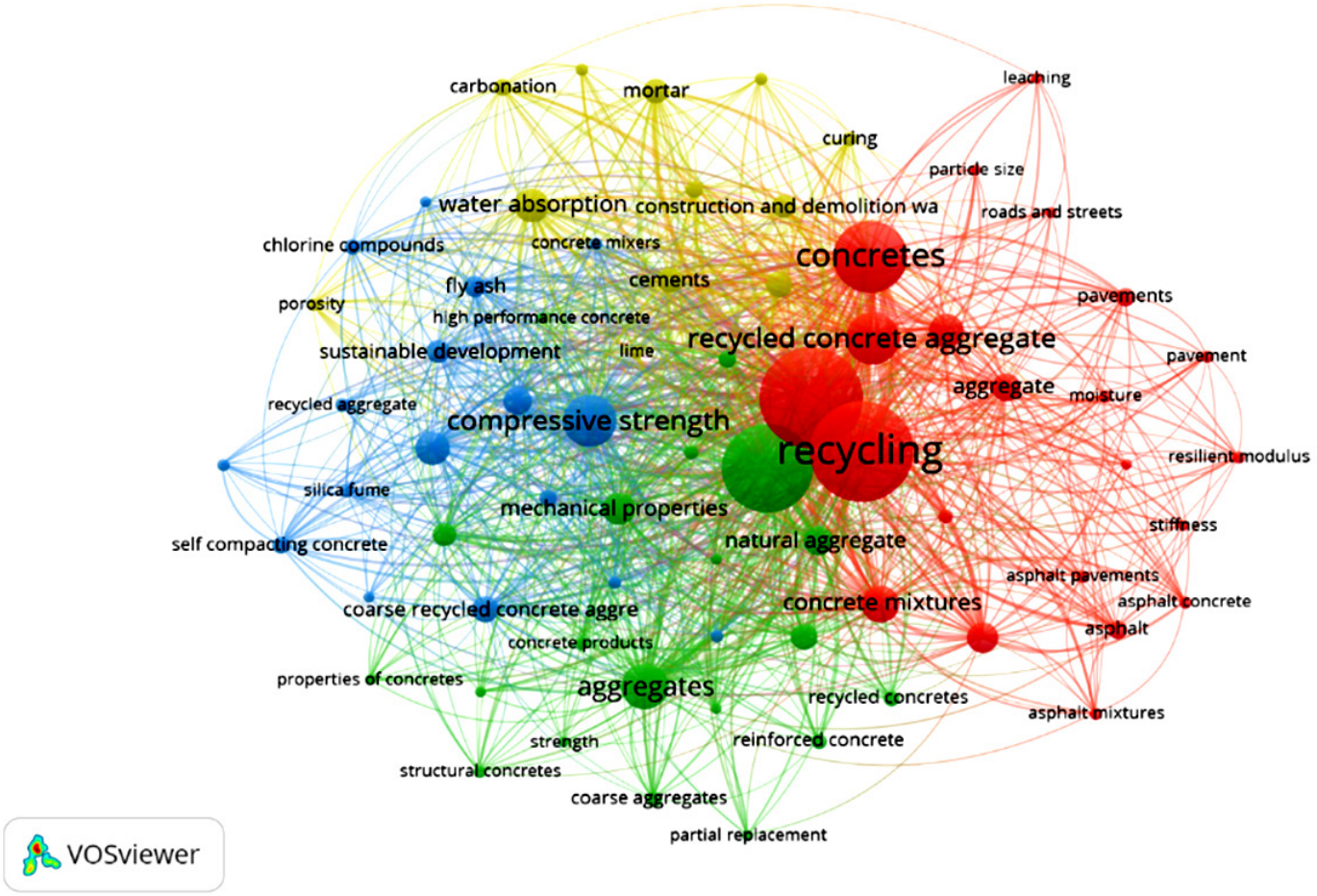

Figure 9: Network visualization map for the most occurring keywords on RCA.

software VOSviewer. The co-authorship analysis process is an essential aspect of the bibliometric analysis technique whereby the level or extent of collaborations between authors on a given topic are examined. Figure 6 shows the network visualization map for co-authorship among RCA researchers. The co-authorship analysis was based on the criteria of a minimum of 8 documents and 2 citations per author. The recovered data showed that out of the 1831 authors, 27 satisfied the search criteria selected the thresholds.

The largest set of connected items consists of 16 clusters with 1-4 items each. The largest or red cluster consists of the De Brito, Evangelista, and Kurda. The second-largest cluster consists of A. Arulrajah and S. Horpibulsuk. The findings showed that the top authors, Arul Arulrajah, Jorge De Brito, and Surinder P. Singh, belong to various networks of authors that have collaborated on RCA studies. Each has collaborated with 2 or more other authors resulting in numerous publications on the subject area. Hence, it can be sensibly surmised that collaboration plays an important role in the output and productivity of researchers, as observed for RCA in this study. The influence of affiliation and their effects researcher's productivity was also examined in this study. The top 5 most active research affiliations on RCA Utilization from 2011 to 2021 is shown on Figure 6. The findings indicate that the listed affiliations have each produced between 18 and 29 publications over the period examined in the study. As observed, the top affiliation is *Instituto Superior Técnico* (IST, Portugal) with 29 published documents, which is largely due to the work of Jorge De Brito who has 16 publications. Further analysis showed that Portugal has two out of the top 5 most prolific affiliations namely IST and *Universidade de Lisboa* (28 publications which rank 3rd in the top 5). The second most prolific affiliation is Dr. B.R. Ambedkar National Institute of Technology in Jalandhar, India with 28 publications, which is largely due to the research productivity of Surinder P. Singh (18 publications).

As stated earlier, the productivity of the outlined researchers may also be down to the availability and accessibility of research funding. Hence, the top funders of RCA studies from 2011 to 2021 were examined to elucidate the productivity or outcome of their various financial supports for the subject area as measured by the total number of publications funded. Figure 7 shows the top 5 funders of RCA Utilization studies between 2011 and 2021 in Scopus.

The findings reveal that the National Natural Science Foundation (NSFC) of China has funded the highest number of published

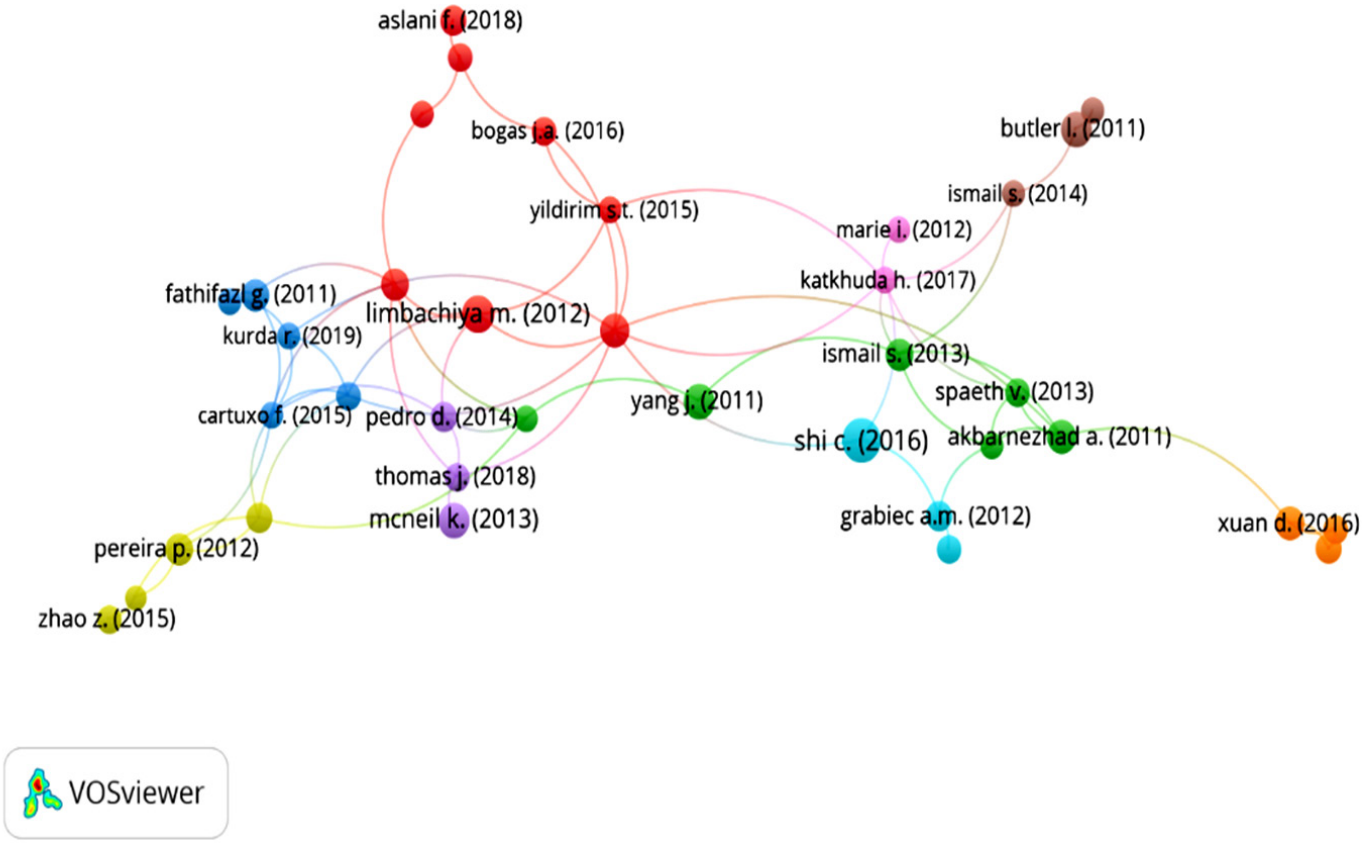

Figure 10: Network visualization map for citations analysis of RCA Utilization (2011-2021).

documents on RCA utilization, with 45 publications. Since none of the top five most productive researchers is based in China, it can be reasonably deduced that the NSFC funds numerous researchers whose aggregated output generates high research and societal impact. The second-largest funder is the National Science Foundation (NSF) of the United States of America (USA) with 20 publications. A critical analysis shows that the NSF has funded the works of authors such as Yahya C. Kurama who is based at the University of Notre Dame in Notre Dame, USA. The Ministry of Human Resource Development (MHRD, India) has funded 17 published documents over the years, particularly the research of Surinder P. Singh of the Dr. B.R. Ambedkar National Institute of Technology in Jalandhar (India). The *Fundação para a Ciência e a Tecnologia* (FCT) based in Portugal is the 5th largest funder of research on RCA utilization. The FCT has funded numerous studies by Jorge De Brito who is based at the *Instituto Superior Técnico*. Overall, the findings indicate that large funding activities of organisations such as the NSFC, NSF, MHRD, and FCT have extensively promoted research and development in China, US, India, and Portugal, respectively. This is evident in the overall output of these nations as shown in Figure 8.

As observed, the top 5 most active countries researching RCA Utilization (2011-2021) are the United States, China, India, Australia, and Malaysia. The presence of the outlined nations on the list can be attributed to the ready access and wide availability of research funding in the outlined countries. For example, the National Science Foundation of the United States has an annual budget of US$7 - 8 billion,[40,41] while the National Natural Science Foundation (NSFC) of China has an annual budget of US$4 billion.[42,43] The annual disbursement of such funds has resulted in numerous projects, publications, patents, and products such as the RCA examined in this study. In addition, the research impact of the subject area has also been greatly enhanced, as evident in the keyword occurrence analysis map shown in Figure 9. The criteria for the VOSviewer analysis were based on a minimum of 25 occurrences of a keyword.

The results show that four (4) clusters are denoted by different colors (red, blue, green, and yellow). The clusters consist of 12-22 keywords with most giant (red) containing words such as "recycled concrete aggregates," "concretes," "asphalt pavements", among others. The most occurring keywords are; "recycled concrete aggregates", which is to be expected due to the search string/query used in the recovery of published documents on the subject area. Another primary occurring keyword is "recycling," which emanates from the process of producing the RCA used in construction. With the large quantities of waste concrete generated by the global construction industry, researchers are attempting to explore more sustainable approaches not only to effectively disposing and managing such wastes but also to valorization. The long-term goal is to sustainably transition from the current linear waste economy to a circular economy to reduce the carbon footprint of the global construction industry.

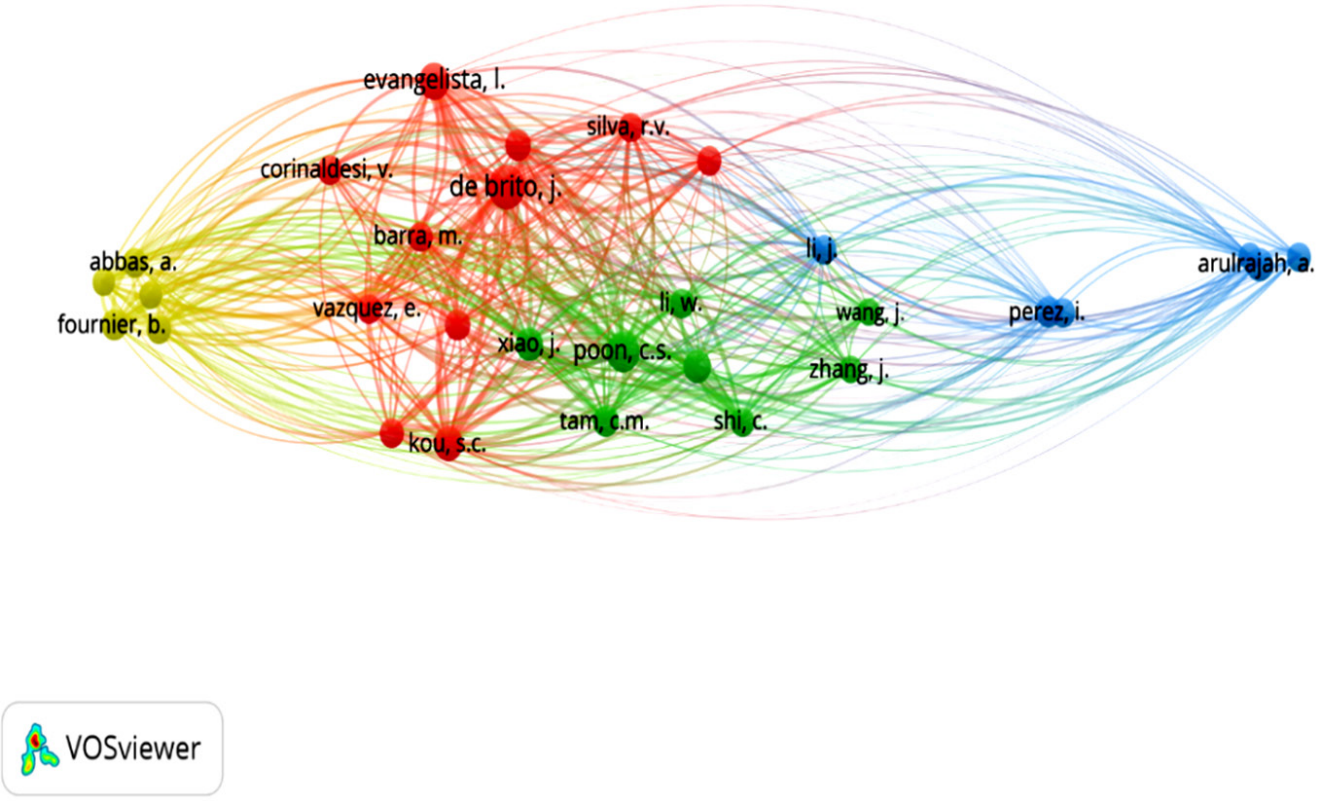

Figure 11: Network visualization map of co-citations analysis of RCA Utilization (2011-2021).

Lastly, it is envisaged that RCA utilization will not only build on recent strides but also spur future research into more sustainable composite materials. Section III presents the significant studies on RCA utilization during the time frame examined in this study.

Top cited publications

The significant studies on RCA utilization were selected based on citations garnered by these studies over the years. Therefore, the top 10 most cited published documents on the subject area were examined as shown in Table 3.

As observed, the top 10 most cited publications on RCA utilization have garnered between 185 and 412 citations over the years. The most cited publication is the review paper "Performance enhancement of recycled concrete aggregate" by Shi *et al.*,[44] The following most-cited publications are; Limbachiya *et al.*,[45] and McNeil and Kang[46] with 289 and 242 citations, respectively. Further analysis shows that 2 out of the top 3 are reviewed, which is to be expected since such papers reportedly gain more citations than other document types in the literature.[54] In addition, the high citations could be attributed to citations and or co-citation among the top or benchmark papers on the field. To examine this, the citation and co-citation analyses of the publications were carried out using VOSviewer.

The citation analysis was based on the following criteria; a minimum number of citations per document of 100. Based on the 807 documents analyzed, a total of 41 satisfied the threshold and were hence selected for network analysis and map visualization, as shown in Figure 10.

As observed in Figure 10, the most extensive set of connected cited publications is 37, which resulted in a total of 9 clusters each with 2-8 items and 63 links. The largest (red) cluster consists of 8 cited publications comprising the works of Limbachiya M. (2012) Verian K.P. (2018) among others. However, the most cited publication is Shi C. (2016) which has 412 citations and 3 links, followed by Limbachiya M. (2012) with 289 citations and 5 links, whereas the third most cited publication is McNeil with 242 citations but just 1 link. In comparison, the publication with the highest number of links is Verian K.P. (2018) with 9 links (208 citations), followed by Katkhuda H. (2017) and Cartuxo F. (2015) with 7 links, respectively. Therefore, the findings indicate there is a correlation between links and high citations, as shown in Figure 10. Similarly, the network visualization map for the co-citation analysis of RCA Utilization publications (2011-2021) shows strong links between the highly cited researchers as shown in Figure 11.

As observed, the top authors such as Jorge De Brito, Arul Arulrajah, Caijun Shi, Chi-Sun Poon, Ignacio Pérez Pérez, among others, have cited each other's studies works in the past as evident in the links between them. Hence, it can be relatively hypothesized that the citations/co-citations between researchers/affiliations works not only play a crucial role in the accumulation of citations but could also serve as a measure of the extent of collaboration.

Table 4: Summary of research and scientific developments on RCA utilization.

References	Study objectives	Year	Summary of findings
Yang *et al.*,[48]	The Effect of adding RCA and crushed clay bricks on concrete properties.	2011	Inclusion of RCA and CCB affects mechanical and physical properties depending on original materials
Pereira *et al.*,[54]	Influence of superplasticizers on RCA-based concrete workability and strength.	2012	RCA with superplasticizers performs better than OPC-based concrete.
Manzi *et al.*,[55]	The short and long-term behavior of structural concrete with RCA	2013	RCA improves mechanical qualities and compressive strength, essential to study the behaviour of structural concretes.
Guo *et al.*,[56]	Examine compressive behavior of concrete with RCA rubber crumb and steel fibre	2014	Compressive strength and stiffness reduce at high temperatures; rubber crumbs increase energy absorption.
Zhang *et al.*,[57]	To examine the effect of carbonation on RCA performance.	2015	Carbonation increases RCA density and strength while reducing water absorption and shrinkage.
Zhao *et al.*,[58]	Investigate the effect of fine RCA on cement mortars	2015	Dried FRCA mortars show higher compressive strength than saturated ones; strength decreases with more recycled sand.
Xuan *et al.*,[59]	To assess the mechanical properties of concrete with carbonated RCA	2016	Carbonation treatment enhances RCA properties and concrete performance, particularly mechanical strengths.
Xuan *et al.*,[60]	To examine mechanical and durability properties of RAC with carbonated RCAs	2017	Carbonated RCAs lower water absorption and permeability, enhancing overall durability.
Kurad *et al.*,[61]	To Investigate RCA and fly ash effect on GWP and strength of concrete	2017	Combined use of FA in RCA concrete provides strength and environmental benefits; optimal FA-RCA ratio improves GWP ratio
Aslani *et al.*,[62]	Develop and characterize high-performance self-compacting concrete (SCC) from waste RCA and granular rubber	2018	Successful SCC production from RCA and rubber; optimized mixes reduce cement usage and maintain good properties.
Kurda *et al.*,[63]	To examine RCA and FA effect on water absorption and electrical resistivity	2019	RCA increases water absorption but lowers resistivity; FA improves both properties, especially with superplasticizers.
Toghroli *et al.*,[64]	Examine RCA and pozzolanic additives in fiber-reinforced concrete	2020	100% RCA increases permeability but reduces strength; SF and NC improve strength; fibre additions enhance performance
Guo *et al.*,[65]	To investigate durability and mechanical properties of sustainable SCC with RCA	2020	FA, slag, and SF mitigate RCA's negative effects, enhancing SCC's sustainability and performance.

Systematic Literature Review

In this paper, a systematic literature review was carried out to examine the research and scientific developments in the subject area. The selection criteria for studies designated for SLW were> 100 citations, publication date (2011 to 2021), and contain keywords "recycled concrete aggregate*". Table 4 presents an overview of the developments in RCA utilization over the years.

DISCUSSION AND ANALYSIS

The results presented in Figures 2 through 11 and Tables 1 through 3 provide a comprehensive understanding of the current state of RCA research. The analysis is structured to highlight the key findings and their implications for the utilization of Recycled Concrete Aggregates (RCA) in construction. Figure 2 shows the publication trends of RCA-related research from 2011 to 2023. The data reveals a significant increase in the number of publications, particularly in the study period. Thus, sustainable construction practice is gaining interest and recognition as evidenced by this trend. The surge (303%) in publications is attributed to the increased environmental concerns and the need for sustainable waste management solutions in the construction industry. Figures 3 to 5 present the co-authorship networks visualized using VOSviewer. These figures demonstrate the collaborative efforts among institutions and researchers. The analysis reveals that certain institutions and researchers play pivotal roles in the network, indicating their contribution and impact on the field. Strong collaboration networks often lead to more impactful

research, as evidenced by the high citation counts associated with these central nodes. Figure 6 shows the keyword co-occurrence network, which highlights the main research themes and topics within the RCA field. Keywords such as 'sustainability,' 'mechanical properties,' and 'environmental impact' frequently co-occur, indicating the primary focus areas of current research. This network analysis helps identify new trends and gaps in the literature, guiding future research directions.

Furthermore, Figures 7 and 8 present the co-citation analysis, which identifies the most frequently cited papers and their interconnections. These figures highlight influential works that have significantly impacted the field. Understanding the co-citation patterns helps in recognizing the foundational research and its impact on subsequent studies. Figures 9 through 11 provide insights into the network density and centrality measures of the co-authorship and co-citation networks. Strong collaboration among researchers is indicated by high network density, while authors and papers that are essential to the network are identified by centrality measurements. These measurements are essential for understanding the dynamics and structure of the research community. Tables 1 and 2 summarize the key studies on RCA utilization, including their methodologies, findings, and contributions These tables provide a summary of the notable studies conducted in the field, demonstrating the various methodologies and outcomes. The summarized studies highlight RCA's adaptability and potential of RCA in various construction applications. The mechanical and physical characteristics of the RCA-based concrete mixes are statistically analyzed and are shown in Tables 3 and 4. The studies show that RCA can improve the workability and durability of concrete while also reducing the material's environmental impact. These results validate the application of RCA as a sustainable substitute for natural aggregates.

Practical Implications and Future Research

The findings of this study provide valuable insights into the utilization of Recycled Concrete Aggregates (RCA) in the construction industry, aligning with global efforts toward sustainability (44). The observed increase in publications on RCA utilization over the past decade reflects growing interest and awareness in sustainable construction practices. This trend is consistent with the objectives outlined in global initiatives such as the Paris Agreement, which calls for reductions in greenhouse gas emissions and promotes sustainable development (15). The identification of major research stakeholders, such as prominent researchers, affiliations, and funding agencies, highlights how collaborative this field of study is (38). Researchers' high productivity is frequently attributed to several variables, such as research funding, institutional and national policy, and access to collaborations. Further analysis revealed that the Ministry of Human Resource Development (MHRD) in China, the United States of America, and India, as well as the National Science Foundation (NSF) and the National Natural Science Foundation (NSFC), are the notable sponsors of RCA research. The research community will be greatly impacted by encouraging researchers to pursue collaboration through the identification of funding sources and institutions. As a result, cooperation between academics and organizations is essential to the advancement of knowledge and creativity in RCA use (29). Stakeholders can advance the adoption of sustainable construction practices by promoting collaborative partnerships and sharing of resources.

According to Nedeljković *et al*.,[45] the examination of highly referenced papers indicates noteworthy advancements in the understanding of RCA use. Şimşek *et al*.,[44] opined that the findings address a variety of subjects, such as material characteristics, environmental sustainability, and performance enhancement. The prominent players in RCA have high rates of co-authorships, co-citations, and keyword occurrences, according to the bibliometric analysis. These metrics point to a high level of collaboration, scientific production, and research impact. Therefore, a study's high citation count highlights its impact on expanding knowledge in the field and indicates its significance and relevance within the research community. Also, the systematic literature review highlights gaps in the literature and offers insights into the state of research on RCA utilization at the moment.

Further studies should also explore innovative applications of RCA in construction and the development of new recycling techniques to enhance its properties and sustainability, future works could also consider how RCA might be used to advance a circular economy and investigate innovative techniques to enhance RCA's functionality in construction applications. When comparing RCA production and utilization to conventional building materials, future research might examine the environmental effects of RCA manufacture and use as well as the long-term performance of RCA-based concrete.

CONCLUSION

This paper, by analyzing publication trends, bibliometric analysis, major research stakeholders, top cited publications, and conducting a systematic literature review of Recycled Concrete Aggregates (RCA) from 2011 to 2021, indicates that publications on the subject area are numerous, highly collaborative, and widely cited. This sheds light on the evolving landscape of RCA utilization in the construction industry. In general, the study revealed that the partial substitution of coarse aggregates with RCA in concrete presents numerous benefits ranging from improvements in mechanical properties to reduction of the carbon footprint, GHG emissions, and environmental burden of the various solid waste streams from the global construction industry. Thus, promoting the use of RCA in construction projects reduces environmental impact, contributes to resource efficiency, supports a circular economy, and develops resilience in the built

environment. By leveraging the insights gained from this analysis, stakeholders, policymakers and practitioners can make informed decisions regarding material selection, project planning, and policy development. It is imperative to note that findings from the paper have practical implications for researchers involved in sustainable construction to continue advancing research, fostering collaboration, and implementing sustainable practices to address the challenges facing the construction industry in the pursuit of sustainability. The novelty of this study lies in its methodological approach, utilizing Scopus's database to perform a thorough scientometric analysis on RCA. This approach provides valuable insight by mapping out the keyword occurrence, co-authorship networks and co-citation analysis thereby revealing the key players and collaborative relationships in RCA research. It also identifies important trends and shifts in research focus and links them to international environmental programs such as the Paris Agreement. However, this analysis has limitations. Its reliance on the Scopus database might not include all relevant publications especially those published in less prominent journals or languages other than English. Similarly, the study focuses on bibliometric and scientometric methods, while useful for identifying trends and patterns, but does not provide in-depth insights into the technical aspects or practical applications of RCA in construction. Also, the analysis is limited to the study period from 2011 to 2021, potentially excluding the most recent advancements made after 2021 or previous foundational work. But, building on the results of this analysis, future research could examine how RCA research develops beyond 2021.

ACKNOWLEDGEMENT

The authors thank King Fahd University of Petroleum and Minerals for the support and facilities that made this research possible

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

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Cite this article: Mahmoud AS, Omar AS. Recycled Concrete Aggregates Utilization in Construction: Publications Trends, Bibliometric Analysis, and Literature Review (2011-2021). J Scientometric Res. 2024;13(3):757-72.