

Review

Bibliometric Analysis of Bio- and Earth-Based Building Materials: Current and Future Trends

Séverine Rosa Latapie * , Ariane Abou-Chakra and Vincent Sabathier

INSA, UPS, LMDC (Laboratoire Matériaux et Durabilité des Constructions), Université de Toulouse,
135 Avenue de Rangueil, CEDEX 04, 31077 Toulouse, France

* Correspondence: slatapie@insa-toulouse.fr

Abstract: The energy and environmental transition in the building sector requires the development and use of low-impact materials. Despite the growing interest in bio-based and earth-based building materials, their widespread adoption is still limited due to a lack of hindsight, as their study is relatively recent. This study aims to contribute to the development of these materials by providing an extensive overview of key contributors (authors, countries, journals) in these fields. Then, the keywords of the corresponding publications were analyzed to reveal the main topics covered to date. First, a broad scale is presented, followed by a focus on sub-categories, specifically raw materials for bio-based building materials and implementation techniques for earth-based ones. Finally, a comparative analysis, with the themes covered by composite construction materials as a whole, completes the study. Using statistical analysis coupled with bibliometric network visualization software, this study provides clear, quantifiable, and objective insights into current trends. Furthermore, it facilitates the identification of new, promising research perspectives and highlights the importance of interdisciplinary collaboration. Physics, modeling, durability and microstructure studies emerge as relevant levers for advancing the future development of these eco-friendly building materials.

Keywords: bibliometric; bio-based building material; earth-based building material



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1. Introduction

The 21st century is the one of global warming awareness. The risks for humanity are major: an increase in natural disasters and their consequences (high mortality, major destruction of buildings and historic sites, etc.), loss of biodiversity, food insecurity, societal conflicts or negative impacts on health (pollution-related pathologies, anxiety, access to drinking water, more pathogens, etc.) [1–4]. As the construction sector is one of the most environmentally impacting [5,6], research into low-impact building materials has been multiplying in recent years. This especially applies to bio-based and earth-based building materials.

Bio-based materials provide performances that contribute to both energy efficiency and building comfort by incorporating agricultural by-products (hemp shiv, sunflower pith or bark, flax shiv, etc.) or wild plants (reed, bamboo, etc.) [7–9]. In the literature, recent reviews of their thermo-hydric performances and applications [10], their fire behaviors [11], the alternative binders used [12], but also the economic and political obstacles to their development [13] are available. No overall analysis has been carried out on this emerging field of research in terms of bibliometric analysis.

Earth-based materials have been used in construction for thousands of years, but their study is relatively new [14]. Their potential is known: low gray energy, low carbon dioxide emissions and recyclability (if not stabilized) [15,16]. Moreover, the hygroscopic capacity of clay-based material ensures indoor hygrometric equilibrium [17]. However, while this eco-material is being used with innovative techniques such as 3D printing [18], it is still difficult to understand its behavior. This presents difficulties of characterization [19]

and reproducibility [20]. Review articles examine the environmental benefits of earth construction [15], the effect of incorporating plant fibers or aggregates [14,21], or characterization and production techniques [22,23]. The social, political, and economic aspects of using raw earth in construction have also been studied [24,25]. However, there is neither a comprehensive study nor a bibliometric analysis of the research carried out to date on this ancestral material.

The choice of treating both bio- and geo-based building materials in the same bibliometric study is a conscious one. These materials share a common history. Although they have only recently been studied, ancestral construction techniques demonstrate the relevance of using plant fibers in earth-based matrices [26–28]. This is due to the complementary nature of the two materials. Earth is a structural material that passively regulates ambient humidity, thus contributing to the building's interior comfort [22]. Plant-based aggregates also have the ability to moderate humidity variations in the indoor environment, and no deleterious effects are observed when plant aggregates are incorporated into a clay base, contrary to observations made for certain combinations of aggregates and cementitious matrices [9]. Consequently, the combined effects of the two materials offer great passive humidity regulation capacities [29]. In addition, incorporating plant aggregates can improve the thermal performance of an earth material [30–32] and limit its drying shrinkage [33]. A growing number of research projects are exploiting this potential by combining the use of plant-based aggregates and raw earth [34–36].

In this light, the purpose of this study is to present a bibliometric overview of the field concerning bio- and earth-based building materials in order to give an overall view of each one. Data concerning these two areas have been processed using two methods: a statistical analysis and the design of visualization maps. The idea is to map each discipline. The results are intended to be used by anyone starting research in one or both of these disciplines. The results are also intended to serve as a reference for experienced researchers in order to identify a new working focus. Several avenues are proposed in this study, but they cannot be exhaustive.

Based on 1778 publications concerning bio-based building materials and 1605 concerning earth-based building materials, this study provides, therefore, a general overview of these emerging research fields. The bibliographic data of these publications were collected from the Web of Science database. This database was chosen because its content is multi-disciplinary [37], enabling a wide range of publications to be taken into account. However, the choice of database may introduce biases [37,38]. However, the large number of publications considered may limit these biases. Again, this study simply sheds new light on general trends in the field of bio- and geo-based building materials and can not represent an exhaustive study.

A preliminary statistical analysis provides an overview of current research activities. A comparison with a field that emerged a few years earlier, composite materials, allowing a comparison of current dynamics and giving an indication of possible future prospects. Then, a more in-depth analysis of the research data was carried out using VOSviewer software. This recent visualization tool can relate and illustrate bibliometric networks [39–42]. Exploring the literature—particularly, the links between authors, themes, and most cited articles—has highlighted several significant points in the fields, as mentioned above. This bibliometric analysis thus underscores major research lines of the scientific community to date. It also identifies grey areas, i.e., topics that have not yet been addressed in order to propose new perspectives of work and help the development of bio- and geo-based materials. Likewise, a more targeted study is carried out on the raw materials for bio-based building materials and on implementation techniques for geo-based building materials.

2. Materials and Methods

2.1. Database: Web of Science

Particular attention has been paid to the selection of publications and corresponding data. The aim was to establish a sufficiently large dataset for conducting a relevant

statistical study. Thus, all publication years from 1900 (database limit) to 2022 were systematically considered. It was also essential to base the study on relevant publications, so retractions were not taken into account. Table 1 summarizes the criteria used to select the publications considered in this review for the primary statistical analysis. They constitute the original database.

Table 1. Web of Science search criteria to extract the initial database.

Topic	Year Published	Number of Publications
"Bio-based building materials"	1900–2022	1778
"Earth-based building materials" or "geo-based building materials"	1900–2022	1605
"Composite materials"	1900–2022	416,745

From this database, a systematic statistical analysis was carried out on bio- and geo-based building materials. This analysis highlights several aspects, including the number of publications per year, the typology of these publications, the countries/authors/journals with the highest publication rates, and the main topics studied. It is worth noting that a publication may at this stage be reported more than once, for example, if several authors have collaborated, or if it covers more than one topic. However, this gives an overview of each discipline considered in this study. The case of composite materials has been approached in a different way, as it provides a basis for comparison.

2.2. Bibliometrics Analysis Software: VOSviewer

VOSviewer [43] is a computer program created in 2010 with the aim of facilitating bibliometric studies and addressing the increasing volume of data [44]. Versions have evolved up to the 1.6.19 one used in this study. The program's algorithm, developed in Java script, is configured to extract bibliometric data from the considered database, enabling the creation of bibliometric network visualization maps. The larger the map element, the more it is cited in the analyzed database. Elements can represent publications, researchers, or research topics, and they are connected pairwise. The strength of the connection is indicated by the width of the line. The links available from a considered database are the following:

- Co-authorship: Refers to publications co-authored by two authors, organizations or countries.
- Co-occurrence: Describes publications in which two keywords appear together.
- Citation: Involves one element (document, source, author, organization, country) citing another one.
- Bibliometric coupling: Measures the number of common references between two documents, sources, authors, organizations or countries.
- Co-citation: Quantifies the number of times items (references, sources, authors) are cited together in the same document.

The database considered should not be too large to allow an effective visualization of the map. It is one of the software's limitations. The analysis of the co-authorship link reveals the primary contributors in a field. The advantage of visualization maps is that they allow us to understand the collaborations between various authors, in addition to their individual contributions. To provide a temporal dimension to the visualization, a time scale can be added. Moreover, the choice of highlighted links is essential for a pertinent analysis. First, the main contributors and their cooperation concerning bio- and geo-based building materials is analyzed with co-authorship links study. Then, in order to bring out the founding works as well as the themes covered in each field, co-citation and co-occurrence links are considered. It enables us to identify themes still neglected or not covered at all and complements the simple comparison with composite materials.

In addition, the visualization maps highlight clusters of elements (depending on the chosen analysis). These clusters require subsequent analysis and interpretation. A wide range of map combinations can be generated from a given database. In this study, the results that seemed most relevant are presented, aiming to provide an overview of the current state in each discipline and suggest new research directions. Keyword analysis is carried out for each category, as well as for sub-categories.

2.3. Work Methodology

To ensure representativeness, a sufficient amount of data is needed, necessitating careful selection in advance. It is also important to ensure that the major works in the green building sector are included. The Web of Science was chosen as the literature database for publication extraction due to its compatibility with VOSviewer software and its recognized relevance for the specific review conducted in this study [37,45]. Data selection played an essential role in this study. In order to retain only relevant publications related to the construction sector, filters within the Web of Science platform were applied. Two distinct working databases, respectively noted “Base BBM-0” and “Base GBM-0”, for bio- and geo-based materials were thus established. Subsequently, the extracted database underwent further processing using spreadsheet software to conduct the statistical study. To create visualization maps, the refined database was imported into the VOSviewer software. From the “Base BBM-0” and “Base GBM-0” databases, the Web of Science platform was used to select publications concerning “sub-categories”. These sub-categories specifically focused on raw materials for bio-based materials and processing techniques for geo-based materials. To summarize the adopted methodology, a visual representation is presented in the form of a flow chart (Figure 1).

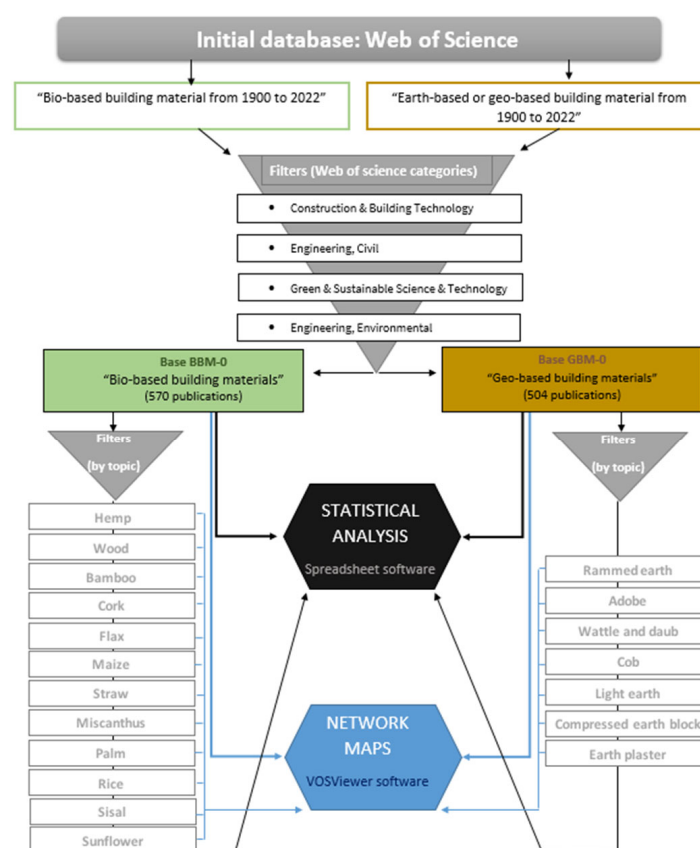


Figure 1. Flow chart of the methodology applied in the study.

To complete the analysis, the same filters (categories) as those described in Figure 1 were applied to the Web of Science publication data corresponding to “Composite building materials”. Only the year 2022 was retained, corresponding to 518 articles, a number compatible with the capabilities of the VOSviewer software.

3. Results

3.1. Preliminary Statistical Analysis

3.1.1. Bio-Based Building Materials

- Increasing number of scientific publications

A small number of research projects were carried out in the late 1990s on bio-based building materials. The field really emerged in the late 2000s (Figure 2).

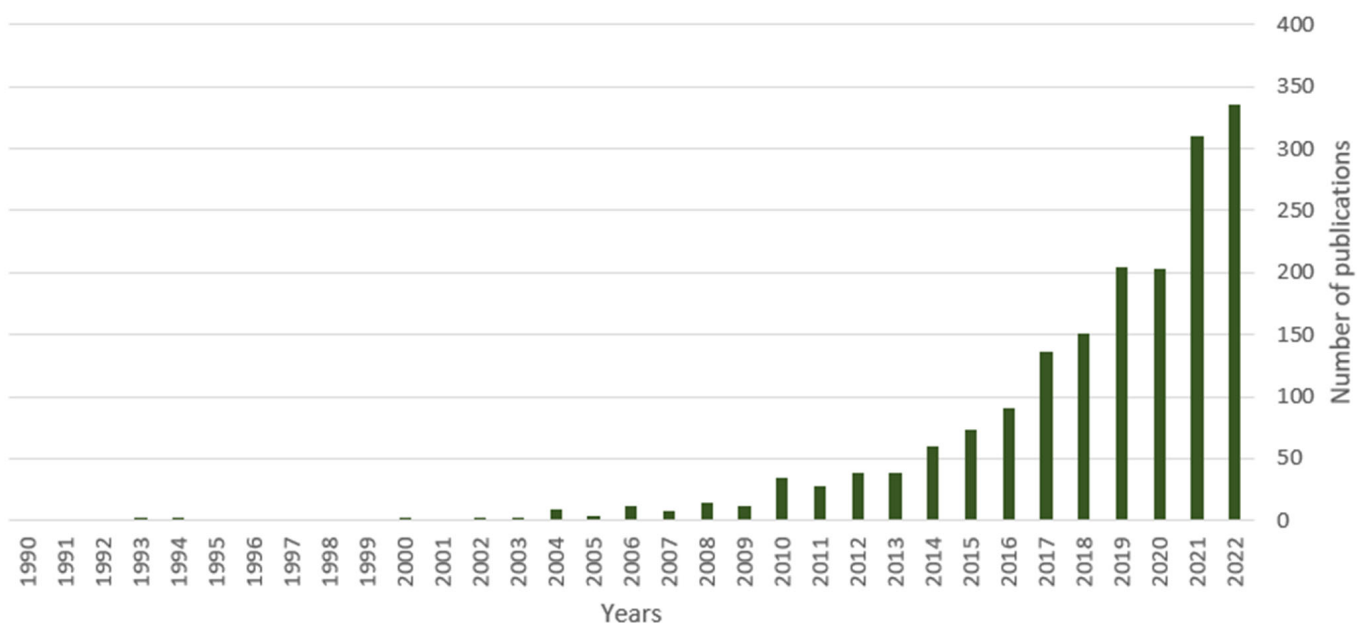


Figure 2. Number of publications concerning bio-based materials between 1990 and 2022 according to Web of Science.

The environmental impact of the construction industry was raised in the literature as early as the 1990s [46–49]. Bio-based building materials, known for their low environmental impact, became the focus of an increasing number of research projects in the following years. The academic community has embraced environmental issues to propose alternative solutions to conventional building materials [50,51]. Reflecting this global awareness, eco-friendly materials have been the subject of a growing number of publications since the 2010s. In 2020, a temporary slowdown in research activity was observed, likely attributable to the global crisis caused by the Covid virus.

However, the last few years, 2021 and 2022, have shown a notable resurgence in research activity within the field of bio-based building materials.

Furthermore, the publication typology reveals a strong tendency to write original articles (Figure 3). Although research activities in this field are relatively recent, review articles represent a relatively large proportion of the publications. In similar proportions, proceedings account for almost 15% of total publications, with a small percentage of book chapters and “other types” of publications including data papers, meeting abstracts and editorial material.

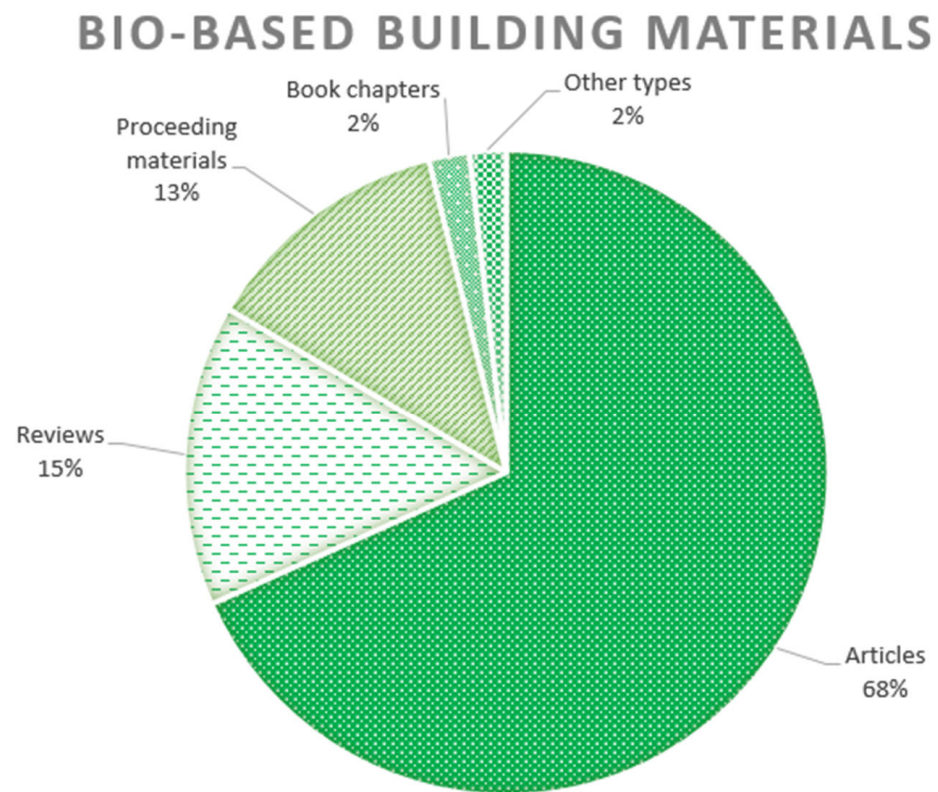


Figure 3. Typology of publications on bio-based building materials between 1990 and 2022 according to Web of Science data.

- Geographic and editorial dynamics

Societal and political issues may have diverged, leading to significant disparities among countries [46,52,53]. Looking closely at the countries publishing the most papers on bio-based building materials, it is interesting to note that European countries are well represented, but they are not the only ones. China, France and the United States are the countries most involved in the academic dynamic in the bio-based building materials sector (Table 2). Regarding authors, a significant portion of publications on the subject of bio-based building materials have been contributed by authors in France and more broadly across Europe (Table 3).

Table 2. Top ten countries of publication concerning bio-based building materials to date.

Countries	Articles
China	309
France	241
USA	225
Italy	147
Germany	139
England	107
India	100
Spain	91
Canada	77
Netherlands	62

Table 3. Most contributive authors in the field of bio-based building materials to date.

Author	Affiliation	Articles
Collet Florence	Université de Rennes 1, Laboratoire de Génie Civil et Génie Mécanique	18
Lanos Christophe	Université de Rennes 1, Laboratoire de Génie Civil et Génie Mécanique	15
Blanchet Pierre	Department of Wood and Forest Sciences, Laval University, Québec, QC G1V0A6, Canada	15
Magniont Camille	Université de Toulouse, UPS, INSA, LMDC (Laboratoire Matériaux et Durabilité des Constructions), Toulouse Cedex 04, France	14
Habert Guillaume	Chair of Sustainable Construction, Eidgenössische Technische Hochschule (ETH) Zurich, Stefano Francini Platz 5, CH-8093 Zurich, Switzerland	13
Pretot Sylvie	Université de Rennes 1, Laboratoire de Génie Civil et Génie Mécanique	12
Lawrence Mike	BRE Centre for Innovative Construction Materials, Department of Architecture and Civil Engineering, University of Bath, BA2 7AY, United Kingdom	11
Langlet Thierry	Laboratoire des Technologies Innovantes (LTI), University of Picardie Jules Verne, Avenue des Facultés—Le Bailly, 80 025 Amiens Cedex 1, France	10
Maalouf Chadi	University of Reims Champagne-Ardenne, GRESPI Laboratory (EA 4694), Reims 51100, France	9

Finally, *Construction and Building Materials* is the journal that publishes the most on bio-based building materials. The other leading journals in the discipline have very similar publication frequencies, between 20 and 40 publications per year (Table 4).

Table 4. Top ten journals publishing articles about bio-based building materials.

Journal	Articles
Construction and building materials	79
Polymers	38
Journal of cleaner production	37
Materials	34
Energy and buildings	32
Journal of building engineering	27
Sustainability	26
Building and environment	25
Industrial crops and products	20
Material today proceedings	20

- Main topics covered

Another valuable aspect of this preliminary statistical study is the list and proportion of topics considered in bio-based building material publications (Figure 4). This demonstrates that fields such as engineering, materials science and chemistry seem to be widely explored, whereas areas like physics, polymer science or environmental sciences (ecology) receive comparatively less attention.

- Focus on raw materials

An additional analysis of the raw materials used as bio-based building materials was carried out (Figure 5).

Not surprisingly, wood has been the most widely published topic for almost 20 years. It is followed by hemp, which is also widely studied, well ahead of all other plant-based aggregates. The prevalence of hemp is attributed to its rapid growth in many climates [54]. Additionally, there is promising research on other raw materials from wild plants (such as bamboo) or agricultural by-products (like maize, sunflower, etc.) [55,56]. Since 2015, there has been a growing interest and diversification in the study of raw materials. Particularly, straw stands out with a relatively high number of publications. For other raw materials, it

is difficult at this stage to differentiate them in terms of publication dynamics. It should be pointed out that, for the sake of clarity in the graphical representation, raw materials with fewer than five publications in the Web of Science database have been omitted. This group includes jute, reed, cork, mussel or oyster shell, barley, rapeseed and sheep wool. Nevertheless, the extensive range of resources studied is probably an opportunity to use local resources minimizing the environmental footprint of building materials [57]. However, a significant challenge arises in ensuring equivalent performance based on the local resource [58]. Overcoming this scientific bottleneck is crucial for advancing the development of bio-based building materials.

BIO-BASED BUILDING MATERIALS

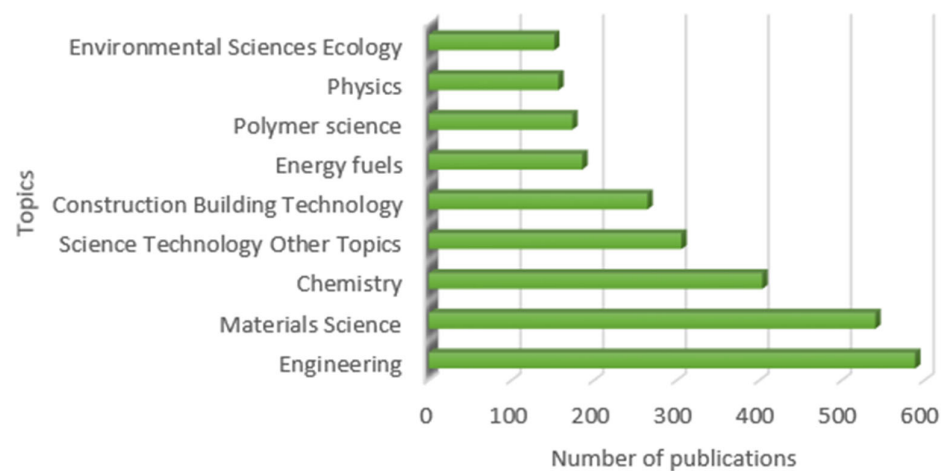


Figure 4. Main topics studied in publications concerning bio-based building materials between 1990 and 2022 according to Web of Science data.

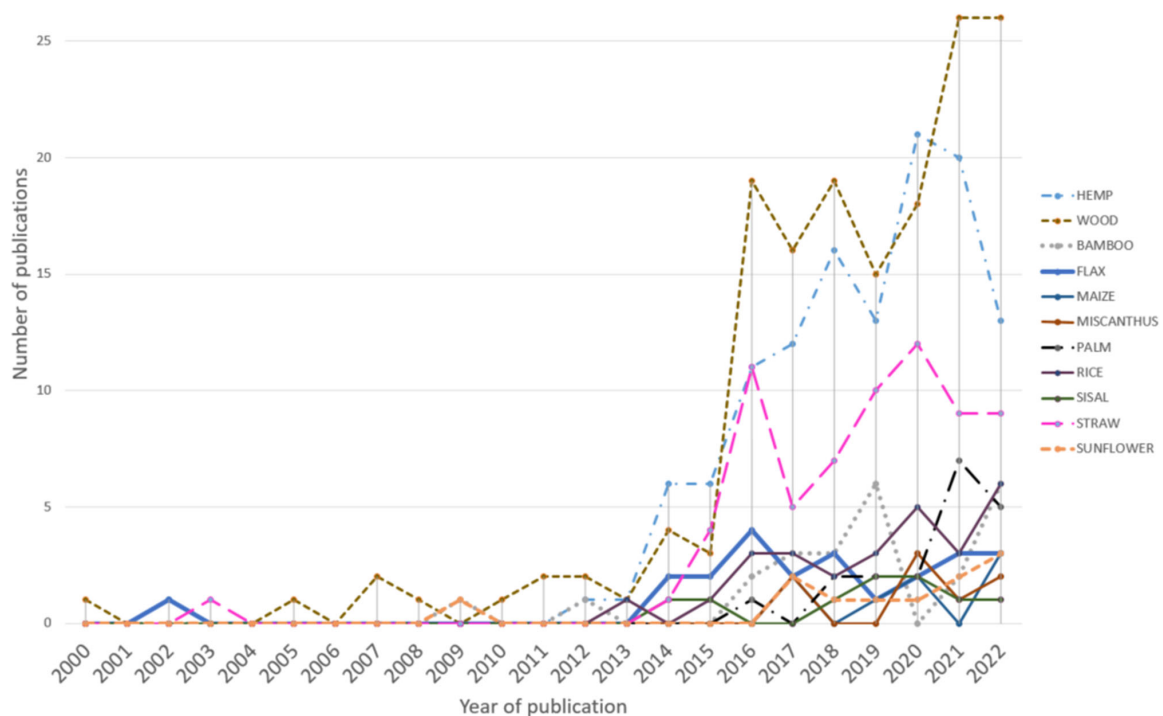


Figure 5. Number of publications for the main raw materials identified in bio-based building materials over the years.

3.1.2. Earth-Based Building Materials

- Increasing number of scientific publications

Research related to raw earth building materials emerged in the 1990s (Figure 6). The number of annual publications has significantly increased since 2005, with dynamics in the following years showing a relatively similar trend to that of bio-based building materials.

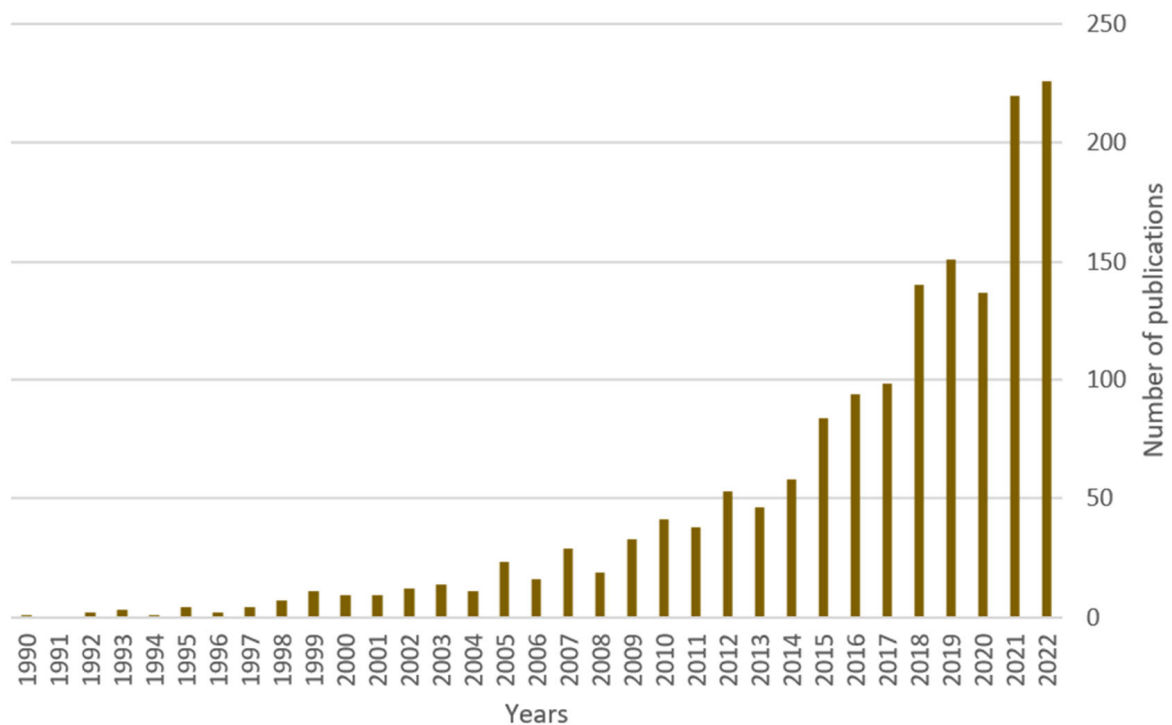


Figure 6. Number of publications concerning earth-based materials between 1990 and 2022, according to Web of Science data.

However, it can be observed that the field of materials using earth as a raw material faces challenges in terms of publication output. In recent years, approximately 30% fewer publications have been published on geo-based building materials than on bio-based ones. It is certainly a multi-factorial phenomenon that combines a biased representation of the material, a lack of incentive policies and sustainability concerns [24,59,60].

The number of publications remained particularly limited in 2020. This was probably due to the slowdown in research activities during the Covid crisis [61]. However, in subsequent years, publications have been on the rise.

The types of publications also logically show a significant proportion of original articles, such as for bio-based building materials (Figure 7). Review articles represent a small proportion, approximately half of what was observed for bio-based materials. In contrast, the proportion of proceeding materials was much higher, roughly twice as high as that for bio-based materials.

- Geographic and editorial dynamics

Despite a large proportion of the population living in earth-based dwellings [62] and the recognized advantages of this material in construction [25], research activities on this subject are concentrated in only a few countries (Table 5). Over 50% of publications come from the following countries: the United States of America, China, France and Italy.

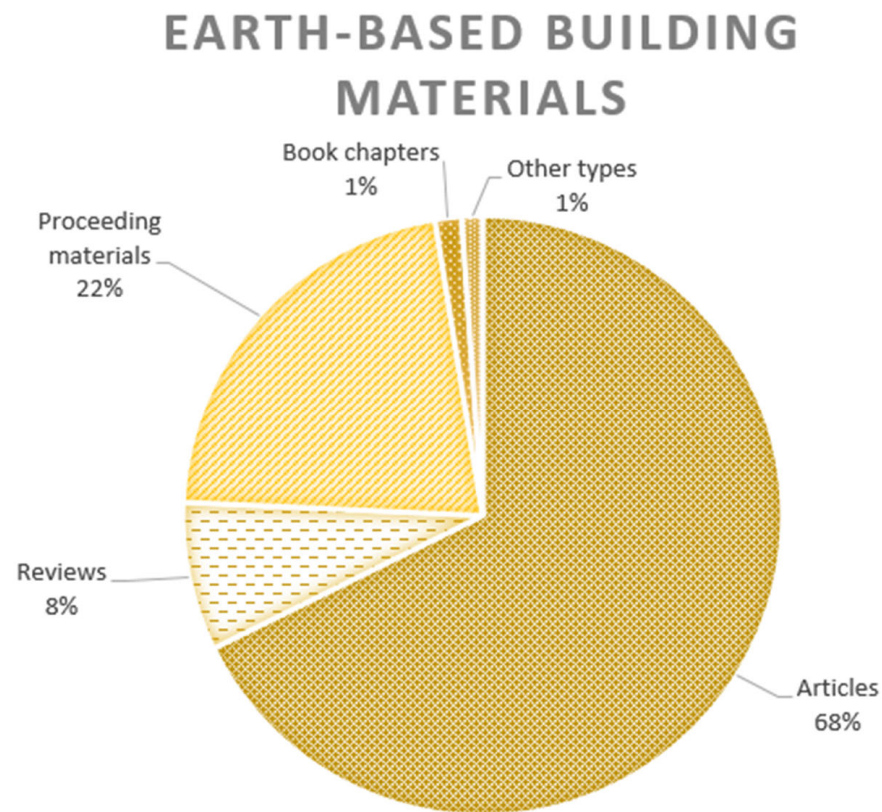


Figure 7. Typology of publications on geo-based building materials between 1990 and 2022 according to Web of Science data.

Table 5. Top ten countries of publication concerning earth-based building materials to date.

Countries	Articles
USA	309
China	291
France	145
Italy	113
Germany	89
England	86
Spain	82
India	80
Portugal	64
Australia	55

The majority of authors in the field of raw earth building materials are Europeans. French authors are particularly active in this domain (Table 6).

Similarly to bio-based building materials, the leading journal for geo-based building materials is *Construction and Building Materials*. It contributes approximately three to four times more than most other journals in the field (Table 7).

- Main topics covered

Interestingly, the main themes covered by the publications closely align with those in bio-based materials. The most represented themes are engineering, materials science and chemistry, while physics and environmental sciences (ecology) remain under-treated (Figure 8).

Table 6. Most contributive authors in the field of earth-based building materials to date.

Author	Affiliation	Articles
Aubert Jean-Emmanuel	Université de Toulouse, UPS, INSA, LMDC (Laboratoire Matériaux et Durabilité des Constructions), Toulouse Cedex 04, France	13
Faria Paulina	CERIS-ICIST and Civil Engineering Department, NOVA University of Lisbon (FCT NOVA), Campus da Caparica, 2829-516 Caparica, Portugal	12
Laborel-Preneron Aurélie	Université de Toulouse, UPS, INSA, LMDC (Laboratoire Matériaux et Durabilité des Constructions), Toulouse Cedex 04, France	11
Magniont Camille	Université de Toulouse, UPS, INSA, LMDC (Laboratoire Matériaux et Durabilité des Constructions), Toulouse Cedex 04, France	9
Humberto Varum	CONSTRUCT-LESE, Department of Civil Engineering, Faculdade de Engenharia da Universidade do Porto, Portugal	8
Niroumand Hamed	Department of Civil Engineering, Faculty of Engineering, Buein Zahra Technical University (IKIU-BZ), Qazvin 34149, Iran	8
Pinto Joao Fransisco	Natural Works, Rua Ricardo Esp. Santo N5 CVD, 1200-790, Lisboa, Portugal	8
Beckett Christopher	Institute of Infrastructure and Environment, School of Engineering, The University of Edinburgh, Edinburgh, UK	7
Zai, M.F.M	University of Reims Champagne-Ardennes, GRESPI Laboratory (EA 4694), Reims 51100, France	6
Hamard Erwan	LUNAM University, IFSTTAR, MAST, GPEM, F-44344 Bouguenais, France	6

Table 7. Top ten journals publishing in the field of earth-based building materials to date.

Journal	Articles
Construction and building materials	63
Sustainability	26
Proceeding of SPIE	23
Journal of building engineering	22
International journal of architectural heritage	18
Journal of cleaner production	18
Inorganic chemistry	17
AIP Conference Proceedings	15
Accounts of chemical research	14
Materials today proceedings	14

EARTH-BASED BUILDING MATERIALS

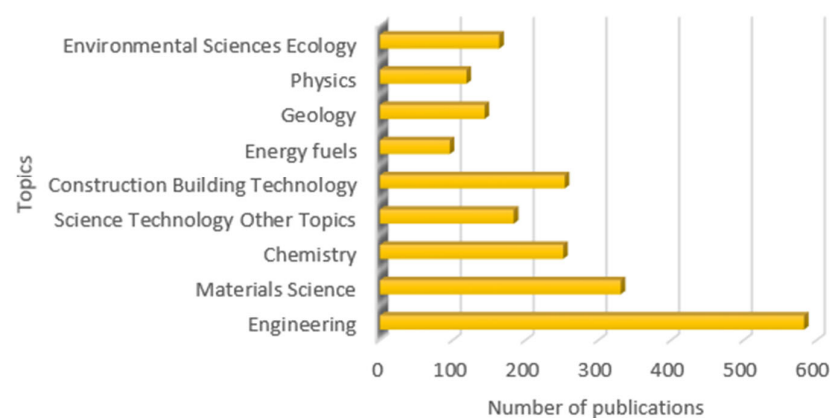


Figure 8. Main topics studied in publications concerning earth-based materials between 1990 and 2022 according to Web of Science data.

This preliminary statistical analysis provides an overview of the research activities carried out on bio- and geo-based building materials since the emergence of these fields.

In particular, it highlights the countries and authors driving this domain. Clearly, Europe emerges as a key driver of the ecological transition, supported by these eco-friendly materials. This leadership can be attributed to contemporary history and environmental concerns.

Concern about global warming, its origins and consequences dates back to the 1990s. In response, the United Nations Framework Convention on Climate Change (UNFCCC) was adopted during the 1992 Earth Summit in Rio de Janeiro [63,64]. Negotiations conducted within this context led in 1997 to the Kyoto Protocol [65,66]. The objective was a 5% reduction in greenhouse gas emissions compared to 1990 levels by 2005. The European Union undertook an 8% reduction in its first commitment period (2008–2012). On 31 May 2002, the Kyoto Protocol was ratified by both the EU and its member states. Europe's commitment was reiterated in 2005 with new objectives, while the United States and China made no secret of their reluctance to ratify the protocol [67–69].

Europe's strong political engagement in the 2000s is certainly at the origin of its leadership in researching environmentally friendly materials [70,71]. The early 2000s coincided with the very beginning of research activities in bio- and geo-based building materials. Since then, Europe has clearly supported innovation and research for a greener and more sustainable society. One example is the EU's Horizon 2020 framework program, with an overall budget of approximatively EUR 70,000 million over seven years (2014–2020) [72]. Another example is the Interreg POCTEFA scheme [73,74] that financed the trans-Pyrenean SAVASCO project, which aims to establish a cross-border value-added chain for corn and sunflower stalks for the construction industry [75,76]. Another example is the Cob-Bauge project funded under the INTERREG VA France (Channel)/England cross-border cooperation program [77,78], promoting raw earth construction.

Today, Europe is aiming for carbon neutrality by 2050 and making it a top priority through the Green Deal initiative [79]. To reach this objective, continued support for research, particularly in the field of eco-construction, will be crucial.

- Focus on implementation techniques

An additional analysis of the implementation techniques and associated studies was carried out concerning geo-based building materials (Figure 9).

While raw earth stands as an ancestral material, our study reveals its recent emergence as a subject of study. According to our study, research into various implementation techniques primarily commenced in the 2010s, with a notable surge in activity for rammed earth a few years earlier. It is worth noting that, since then, all techniques have followed a very similar trend, with the exception of rammed earth, which exhibited nearly double the scholarly attention in 2022. This growing interest can be attributed to architects valuing its aesthetic appeal or its potential for prefabrication, aligning with contemporary demands [80–82].

3.2. Comparative Study with Composite Building Materials

To further enhance the analysis, a comparison with activities carried out in the field of composite materials has been included. This section provides an overview of research areas in bio- and geo-based building materials that could contribute to their development by identifying those that have been promising for composite materials.

3.2.1. Evolution in the Number of Publications on Composite Materials

It seemed interesting to compare the evolutionary dynamics of bio- and geo-sourced materials with a research field that emerged a few decades earlier, in the 1960s—composite materials. To take a global view and appreciate the research dynamics in these materials, the statistical study was not limited to composite materials used in construction. All sectors have been considered here (Figure 10).

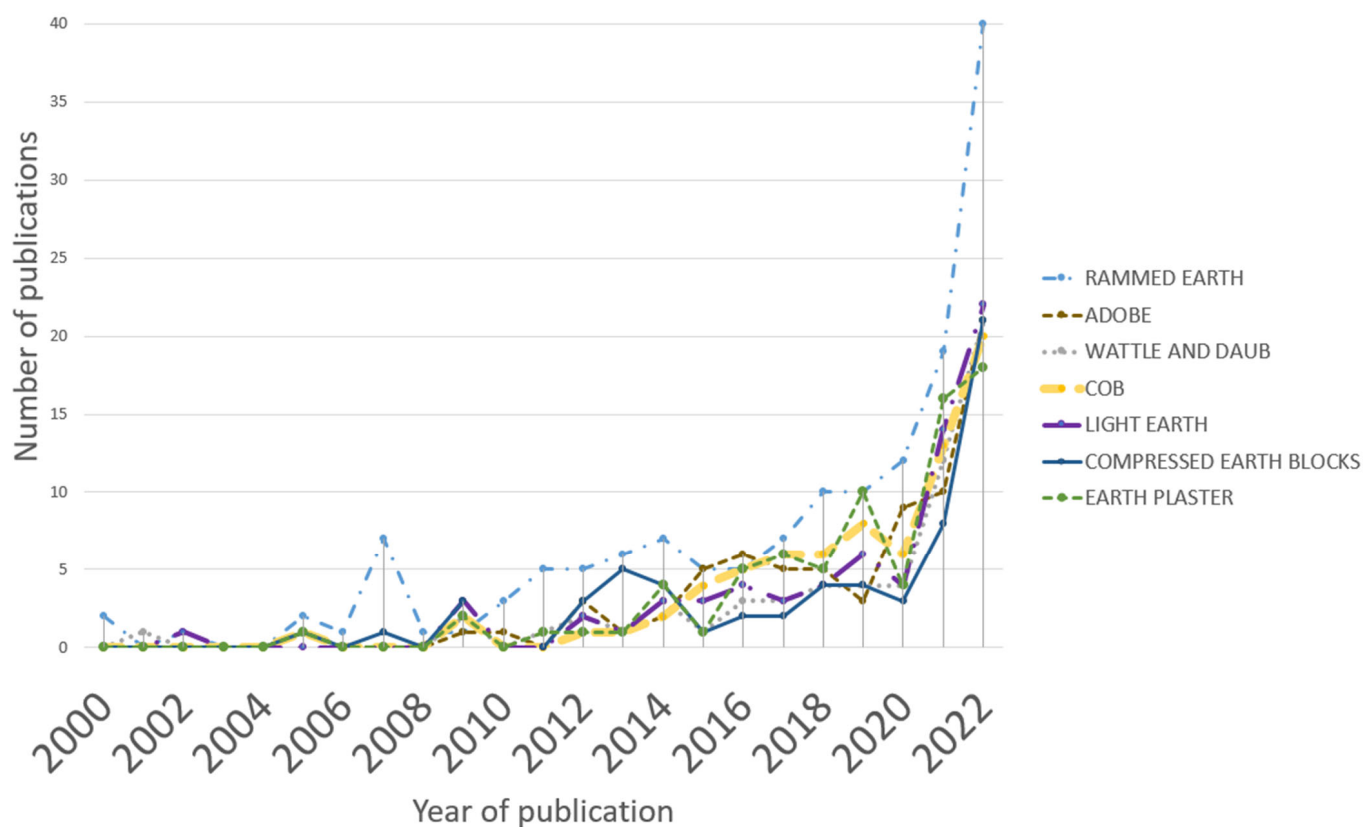


Figure 9. Number of publications for the main implementation techniques of geo-based building materials over the years.

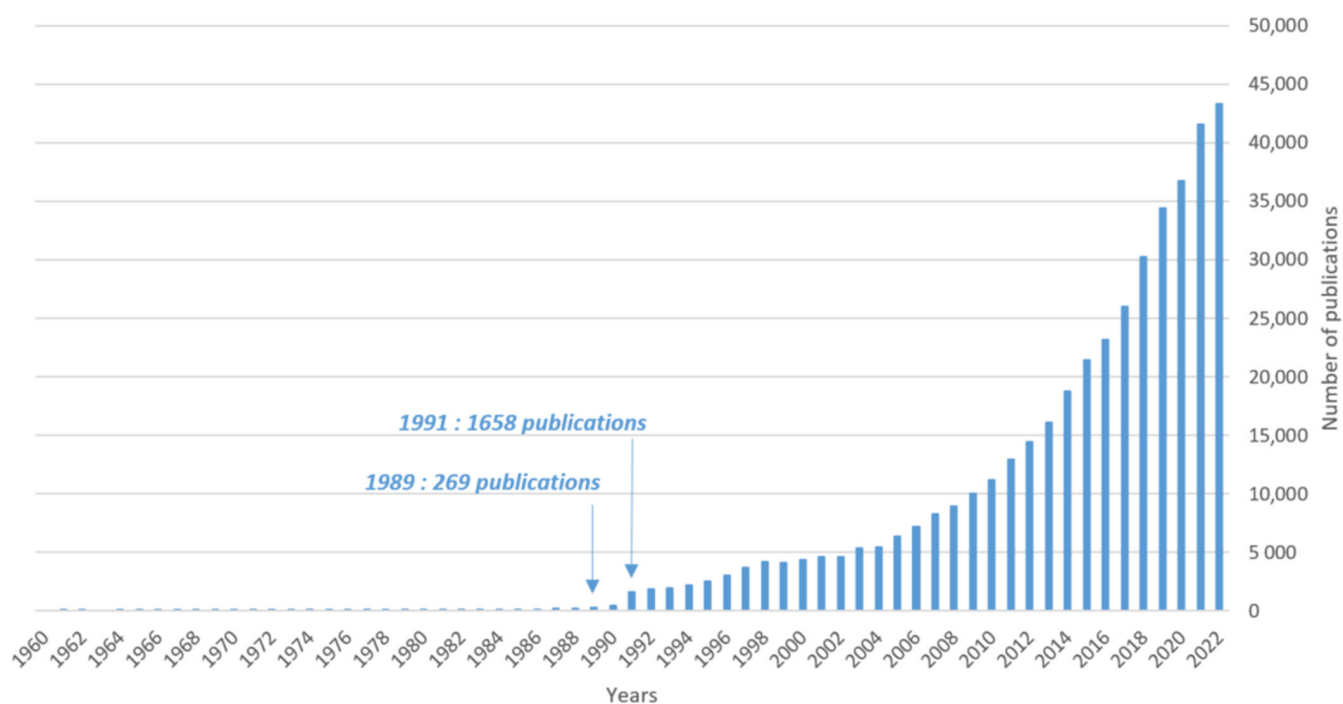


Figure 10. Number of publications concerning composite materials between 1960 and 2022 according to Web of Science data.

- Obviously, the number of publications is extremely high, providing an overall perspective. What is striking is the number of publications, which increased more than six-fold between 1989 and 1991. It is legitimate to question the reasons for this major breakthrough in composite materials and related work in those years.
- The 1990s marked the beginning of the computer age. Since then, computer networks have been driving progress in science and engineering [83]. One possible explanation for the inflection point in publication growth is the development of computer technology. Before the 2000s, numerous publications incorporating computerized tools were noticed [84–87].

3.2.2. Emerging Themes and Tools for New Developments

In order to assess the above hypothesis, the evolution of the number of publications related to composite materials dealing with modeling, which requires the use of computer tools, was observed around the year 2000 (Figure 11).

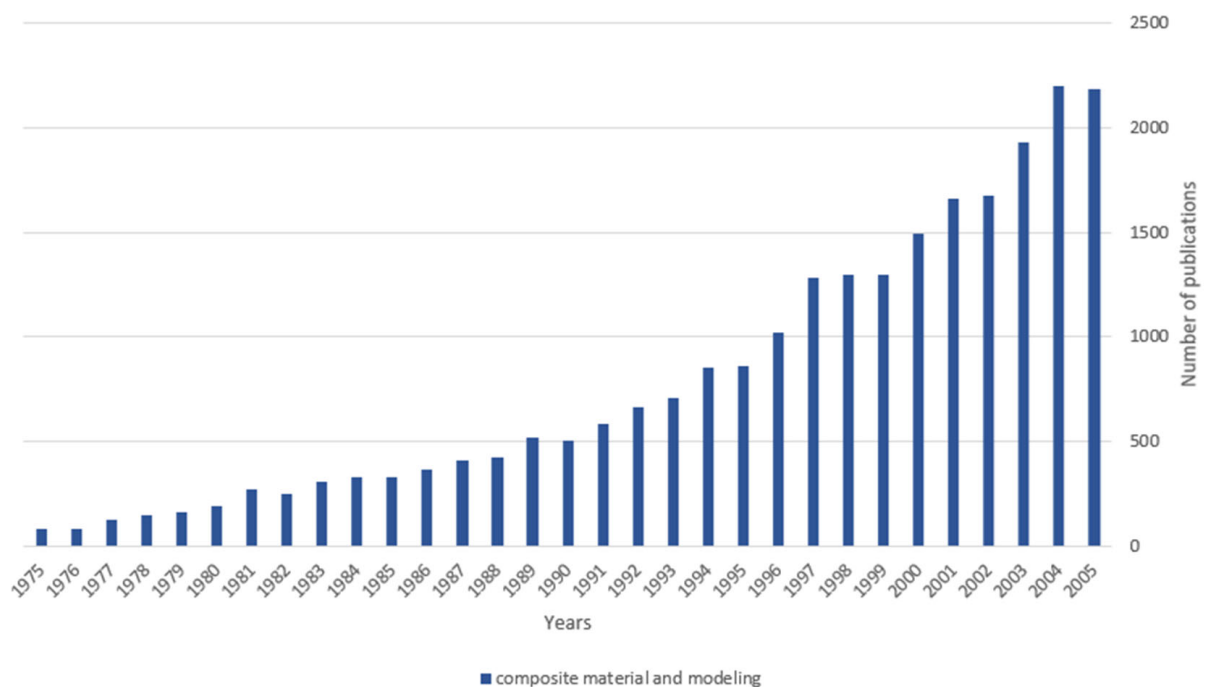


Figure 11. Number of publications concerning modeling and composite materials in the 2000s according to Web of Science data.

Between 1990 and 2000, the number of research projects focused on modeling composite materials tripled. The use of IT tools was undoubtedly a major lever in the development of these emerging materials.

The exploration of new and promising research themes could also explain the rapid growth in the number of publications. A comparative study of the themes studied before and after 1990 were carried out (Figure 12).

This comparison reveals that the fields emerging after the 90s were the hard sciences, particularly chemistry and physics. They have respectively risen from 8th and 7th place to 3rd and 4th place in the list of main themes covered. One of the mainsprings for the development of composite materials is probably a better understanding of their physico-chemical behavior.

3.2.3. Eco-Materials: What about Modeling and the Hard Sciences?

The subject of modeling in bio- and geo-based building materials seems to be in its infancy, as indicated by the number of publications over the years (Figure 13).

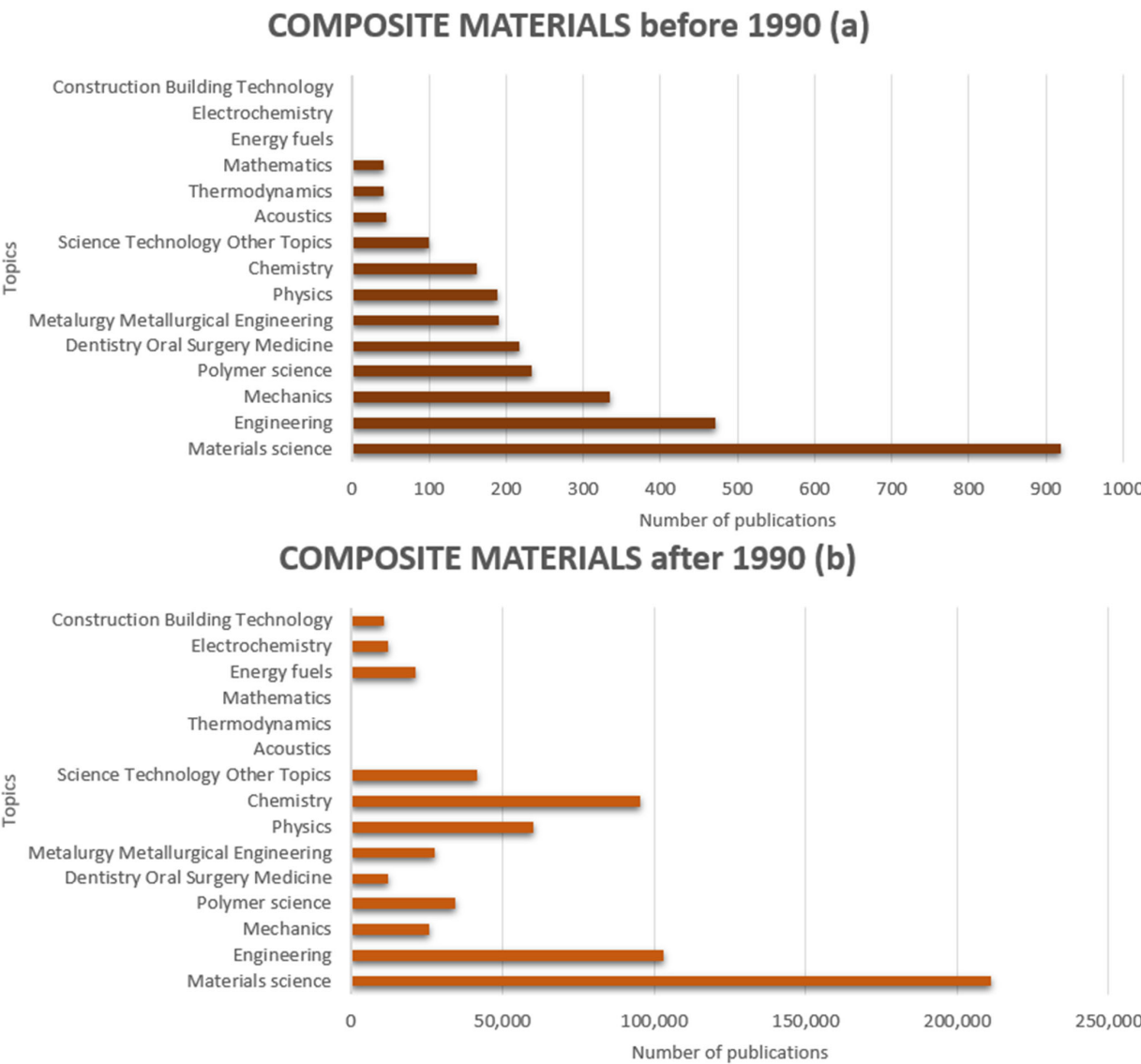


Figure 12. Main research areas studied in the field of composite materials from 1960 to 1990 (a) and from 1990 to 2022 (b) according to Web of Science data.

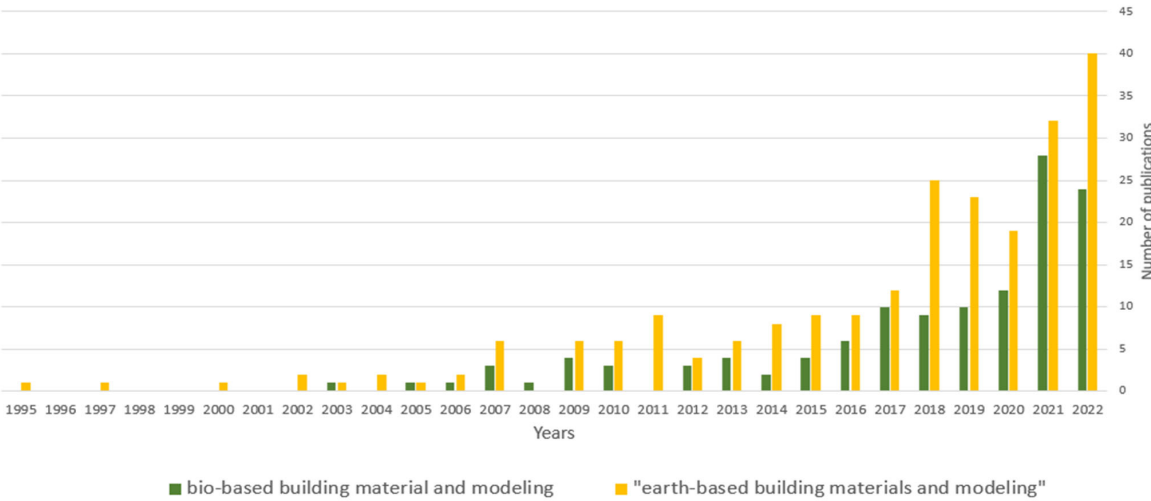


Figure 13. Number of publications concerning modeling and bio-based or geo-based building materials according to Web of Science data.

The number of publications related to modeling in the two research areas is increasing. Cumulatively, it represents 7% of the total number of publications for bio-based building materials and 15% for geo-based ones. By comparison, modeling is involved in 6% of publications on composite materials. However, if the focus is limited to construction-related composites: from the 19,459 publications reported by Web of Science, 5166 deal with modeling, accounting for over 26%. This suggests that modeling is still underexplored with regard to bio- and geo-based building materials.

Secondly, the percentage of works exploring physics and chemistry has been determined as a proportion of the total number of publications for each research area (Figure 14).

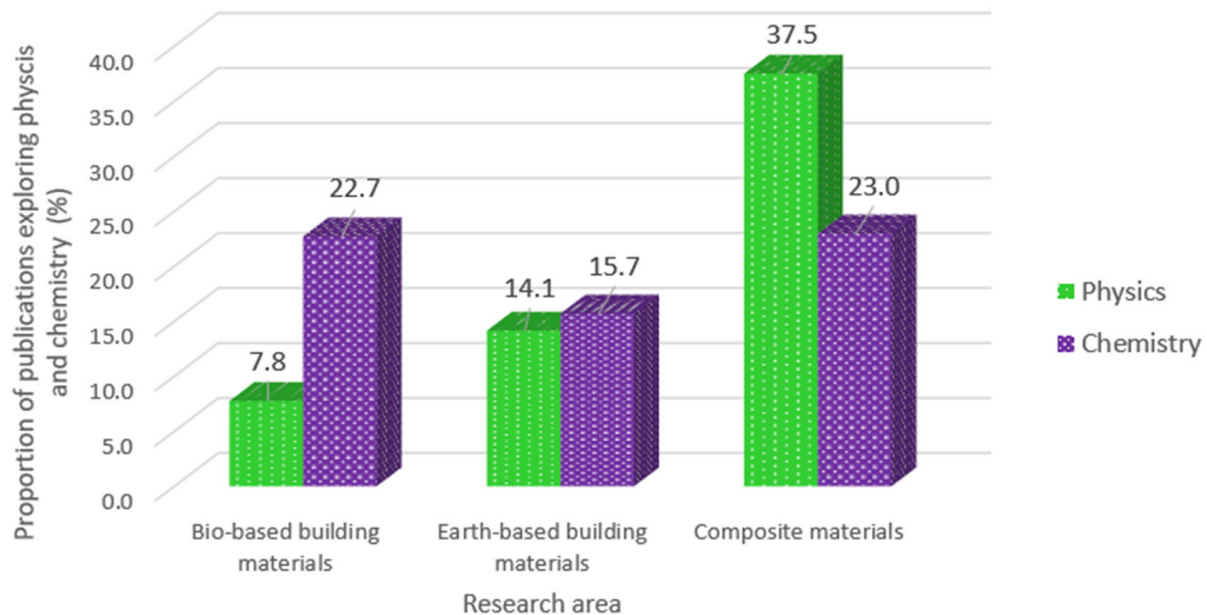


Figure 14. Proportion of publications, from 1900 to 2022, dealing with physics or chemistry in different types of materials according to Web of Science data.

Chemistry's contribution to bio-based building materials and composites is very similar. It is slightly less represented for raw earth building materials. However, the notable disparity lies in the field of physics. Physics appears to be relatively underexplored in the field of eco-materials, whereas it plays a significant role in more than a third of publications in the composite domain.

In conclusion, it appears that physics and modeling tools are probably the levers to be considered for improving knowledge of bio- and geo-sourced building materials and contributing to their development.

3.3. Bibliometric Networks

3.3.1. Bio-Based Building Materials

- Main authors and their collaborations

The analysis of the co-authorship link reveals the main contributors in the field of bio-based building materials (Figure 15). The advantage of visualization maps is to enable an appreciation of the collaborations between the different authors, in addition to their individual contribution. To provide a temporal dimension to the visualization, a time scale can be added.

This map highlights the main authors identified in the previous study. Collaboration between major authors appears to be generally low, especially if they have different affiliations. The only notable exception is the recent collaboration between colleagues from the University of Toulouse and Rennes. Moreover, according to these results, it appears that international cooperation is currently limited.

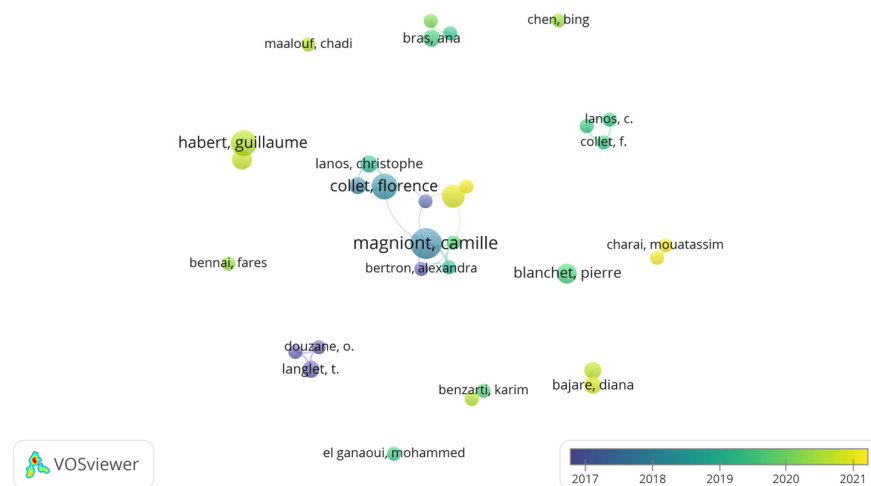


Figure 15. Co-authorship networks of authors (with minimum of five publications) concerning bio-based building materials, with time scale over the last few years.

- Founding works

An interesting feature is the possibility of identifying the founding works of the discipline. The analysis of reference co-citation links reveals the most widely cited and associated works (Figure 16). For better readability of references and their importance, the visualization density map has been preferred to the visualization network map.

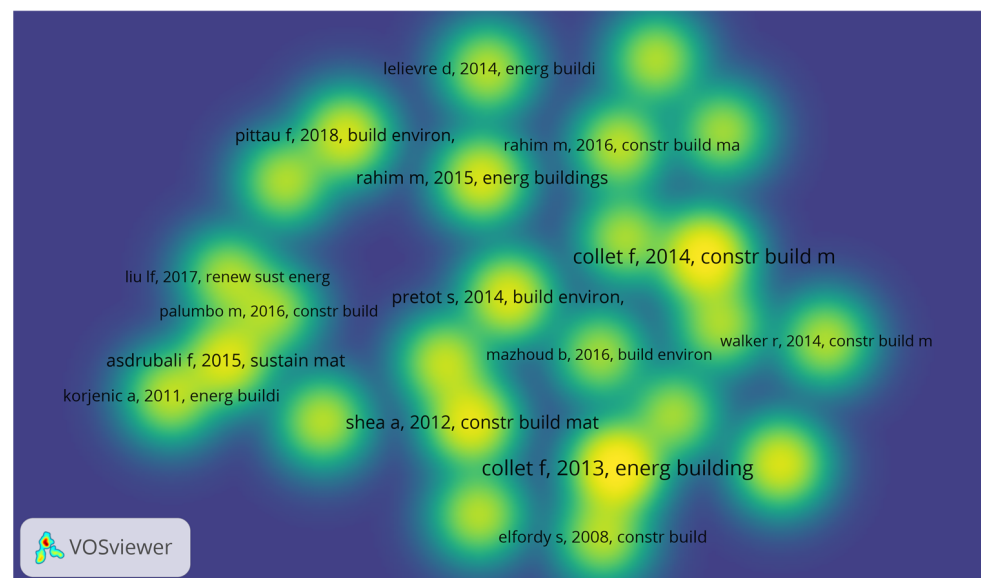


Figure 16. Founding works concerning bio-based building materials [88–102].

This approach can be very useful for targeting the main works to be consulted when beginning a research work on bio-based building materials. It can be pointed out that these publications are globally concentrated around the year 2015.

- Key themes in the literature

Analysis of the co-occurrence of keywords in the 570 selected publications (cf. Section 2.2) reveals four clusters, representing the four main themes explored in the literature (Figure 17).

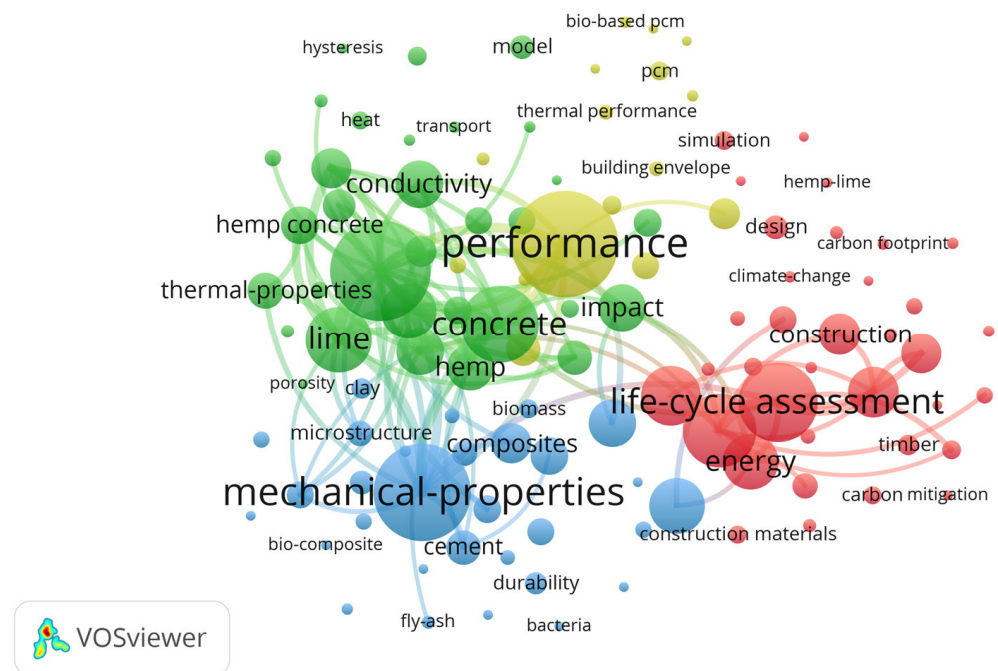






Figure 17. Co-occurrence networks of keywords concerning bio-based building materials.

The analysis of the clusters generated by the VOSviewer software allows their identification (Table 8). However, it is worth mentioning that this is not always easy, as some themes are shared by several clusters, such as mechanical properties. Therefore, the general theme assigned to each cluster is an interpretation based on the articles identified in each cluster.

Table 8. Main areas of research according to cluster analysis.

Cluster	Associated Color	General Theme
1		Environmental impact
2		Thermo-hydric behavior
3		Mechanical properties
4		Building-scale performance

The complexity of bio-sourced materials may explain the interweaving of the different themes. Nonetheless, these research topics enable one to identify the current areas of research. Interestingly, none of the clusters directly refers to the hard sciences like physics, and the concept of “model” appears only modestly in the cluster related to thermohydric behavior.

- Focus on main raw materials
- In order to provide a closer insight into the contributions made to date on the main raw materials identified in Section 3.1.1, an analysis of keyword co-occurrence was carried out within the relevant publications. The visualization includes a time scale to emphasize trends over recent years. For the sake of relevance, this section focuses exclusively on primary resources with more than 10 publications each: hemp, wood, bamboo, flax, palm, rice, straw, sunflower (Figure 18).

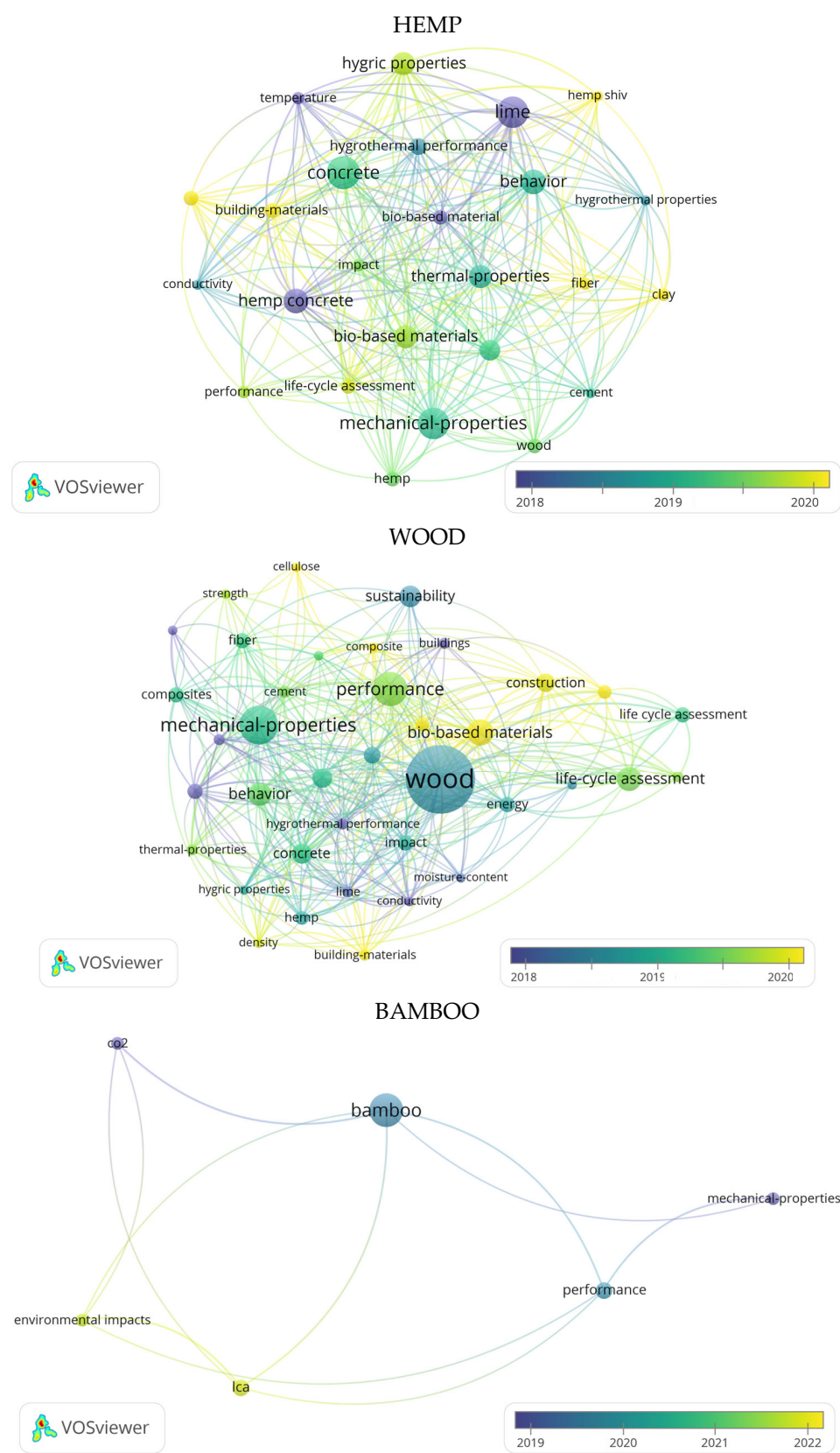


Figure 18. Cont.

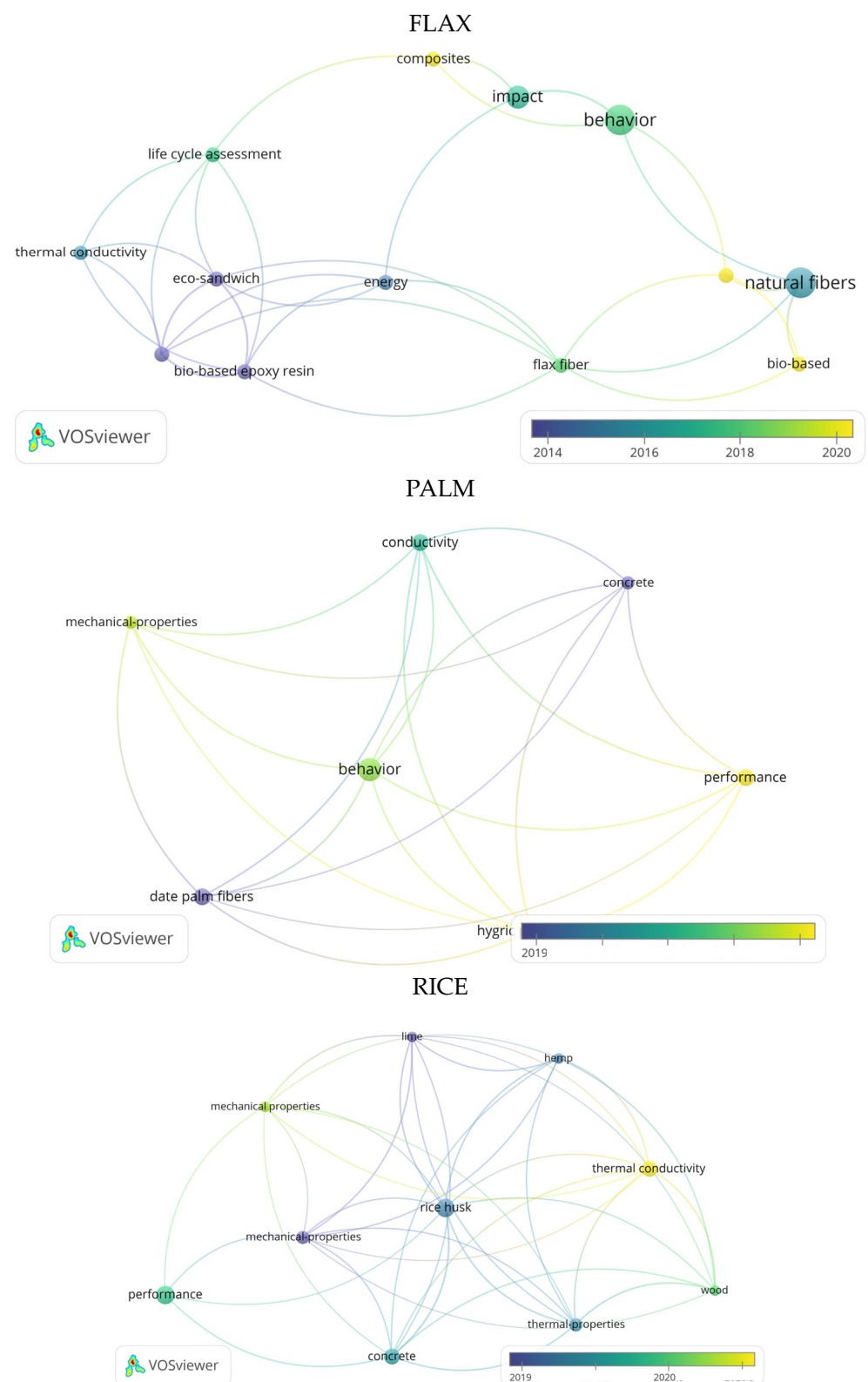


Figure 18. Cont.

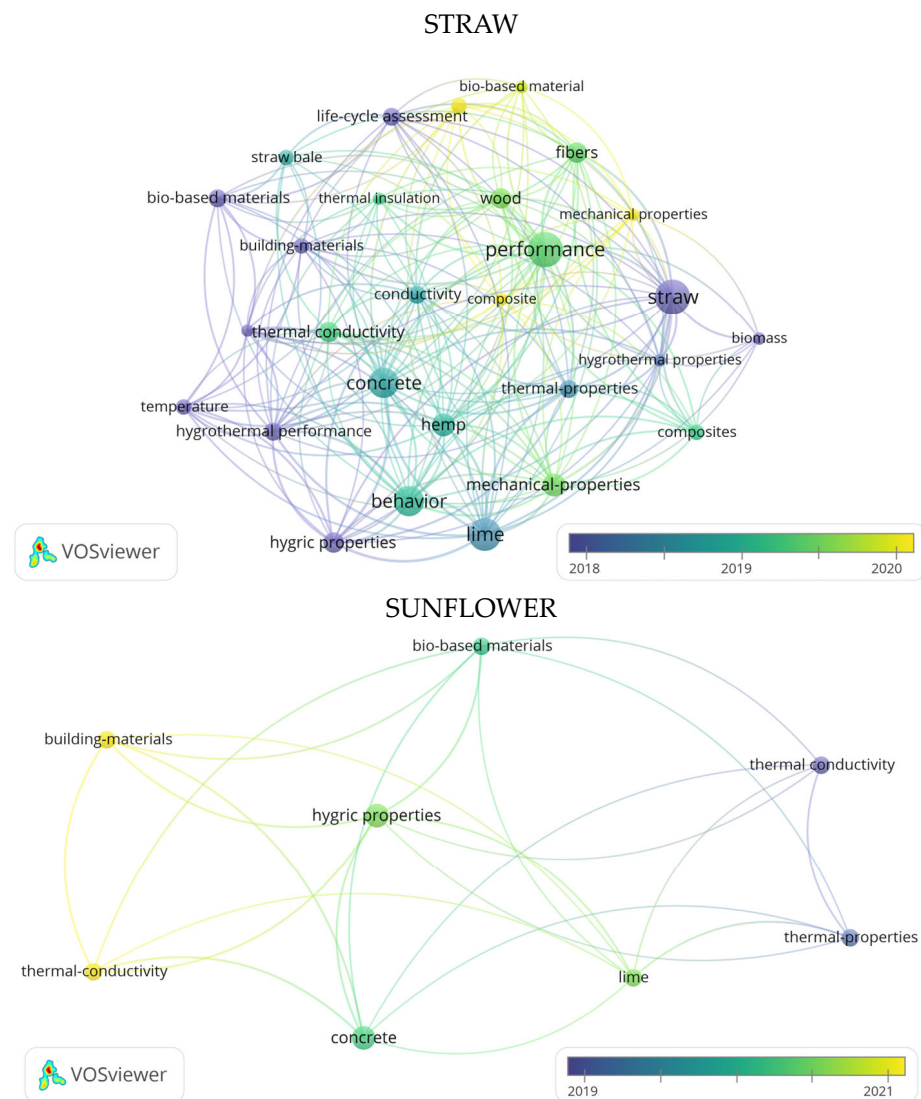


Figure 18. Co-occurrence networks of keywords concerning publications about the most widely studied implementation techniques in the literature.

These maps highlight the keywords corresponding to the topics mainly studied for each raw material. The notion of life cycle assessment appears to be one of the most discussed subjects in the literature concerning the raw materials considered. However, this subject does not emerge for some of them, thereby highlighting new areas of work. This multi-criteria analysis enables us to objectively demonstrate the benefit of using bio-based materials compared to conventional ones [7]. Notably, the concepts of performance (thermal, hygrothermal, mechanical) are well represented, in line with their function in construction. Wood, hemp and straw naturally yield a richer array of keywords due to their extensive research focus. Wood, used as a structural element, is highlighted by the keywords “timber” and “mechanical properties”. Hemp shiv, often added to a binding matrix (lime, cement) for hemp concrete, is highlighted by the map. An earth-based binder matrix is also possible, which explains the keyword “clay”. Straw, used for insulating wood structures or as a substitute for hemp in plant-based concrete, offers properties very similar to those of hemp. This explains the great similarities between the maps for straw and hemp.

All of the topics covered in wood, hemp and straw are inspirational sources for continuing to develop our knowledge of other raw materials applicable to bio-based building materials. These include the following topics:

- “Cellulose”: linked to the chemical composition of the resource, particularly relevant to wood as a primary chemical compound.
- “Moisture content”: in relation to water adsorption by the material and potential pathologies arising under such conditions.
- “Sustainability”: referring to the evolution of a material’s properties under various stresses, including temperature and relative humidity variations over its lifetime.
- “Energy”: related to the overall energy efficiency of the building, i.e., covering a more global scale than that of the material or the wall.

It should not be overlooked that the development of bio-based building materials also requires taking into account the diversity of resources, which probably has an impact on their use properties [103,104]. Lastly, the use of local raw materials necessitates the establishment of effective harvesting and recovery procedures [76].

3.3.2. Geo-Based Building Materials

- Main authors and their collaborations

The main contributors in the geo-based building materials sector and their collaborations are presented (Figure 19).

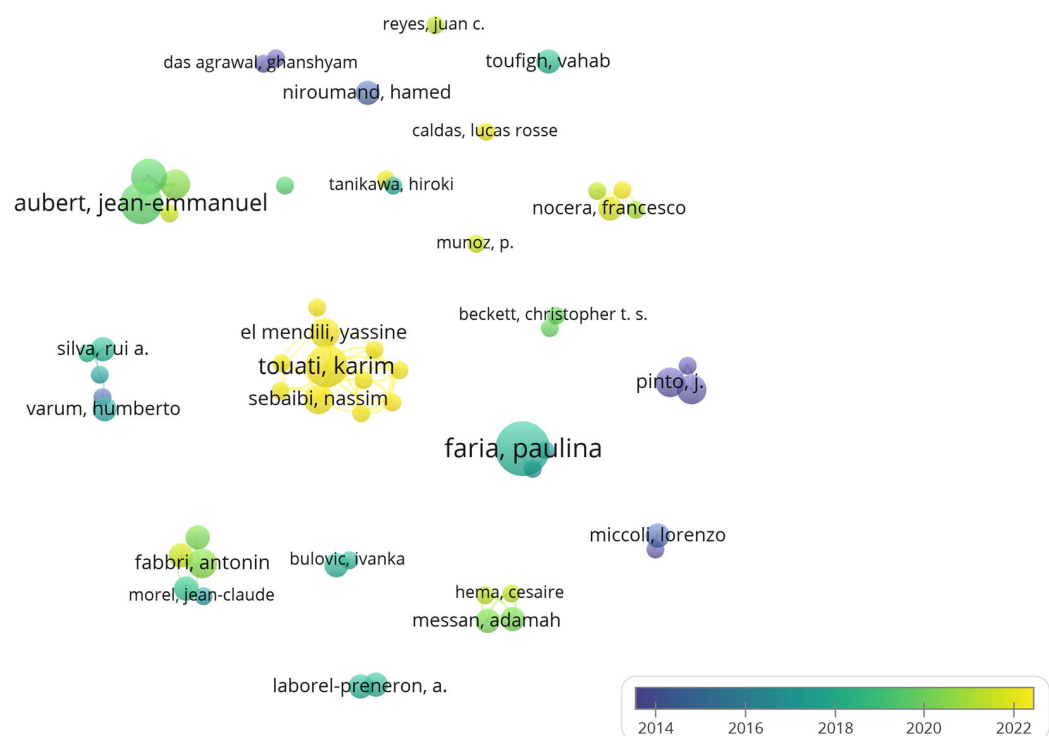


Figure 19. Co-authorship networks of authors (with minimum of three publications) concerning geo-based building materials, with time scale over the last few years.

According to this map, collaboration between authors appears even more limited than that for bio-based building materials. The few collaborations that are visualized mostly involve authors from the same affiliation. The time scale shows that the number of collaborations have been multiplying very recently. No significant European or international collaborations are to be reported, since they involve authors from the same country and often from the same affiliation.

- Founding works

- The most frequently cited research works date from the 1990s to 2000s (Figure 20). These works are considered foundational in the field.

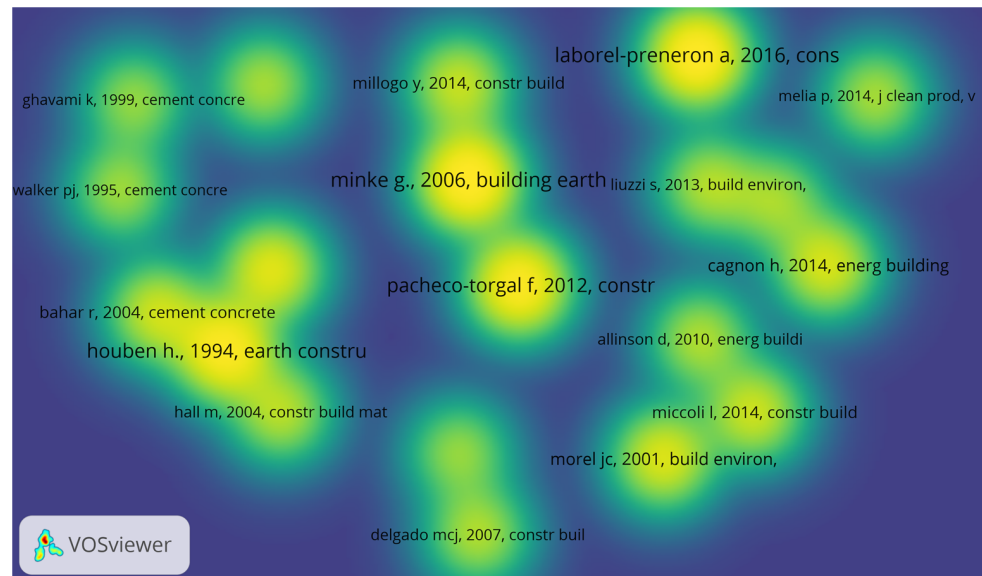


Figure 20. Founding works concerning geo-based building materials [14,15,51,105–117].

Similarly to bio-based materials, this list of works can help identify fundamental results in the field of raw earth building materials research.

- Co-authorship links

Analysis of the co-occurrence of keywords in the 504 selected publications (cf. Section 2.2) reveals four clusters, i.e., four main themes explored in the literature (Figure 21 and Table 9).

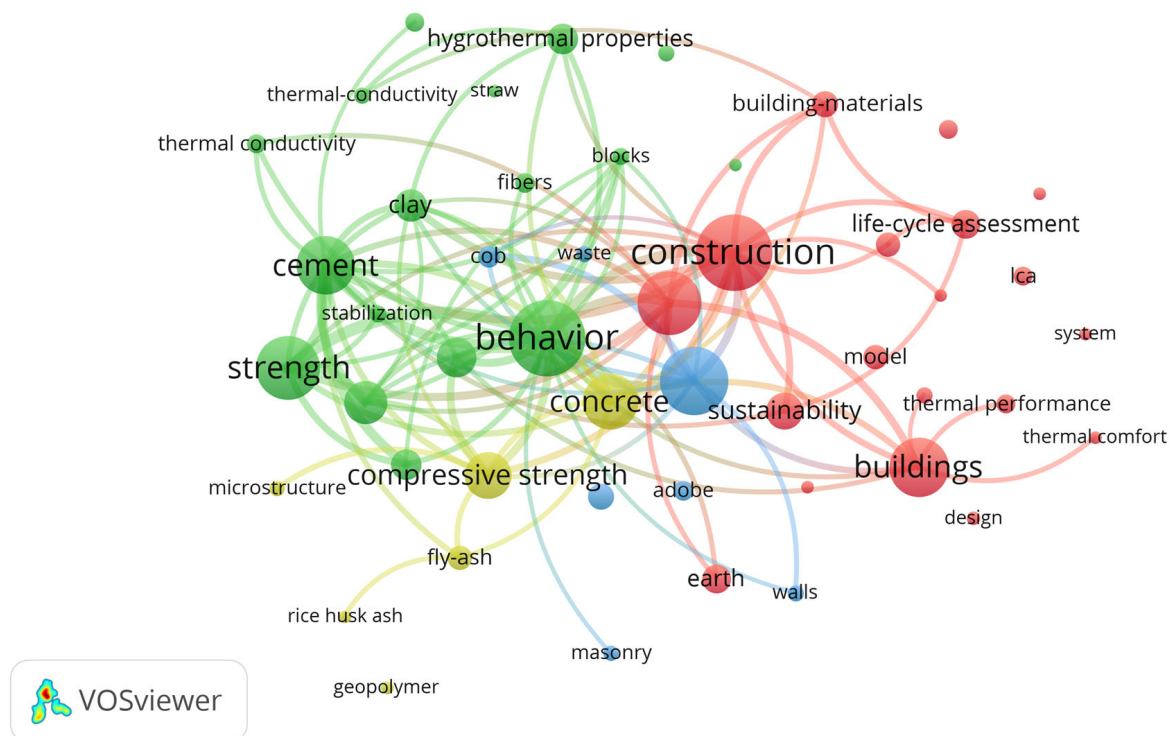


Figure 21. Co-occurrence networks of keywords concerning geo-based building materials.

Table 9. Cluster analysis (in decreasing order: n°1 corresponds to the greatest number of publications).

Cluster	Associated Color	General Theme
1	●	Environmental impact
2	●	Thermo-hydric behavior
3	●	Construction techniques
4	●	Mechanical behavior

The keywords mainly associated with the research work do not highlight strong themes related to the hard sciences. It is reasonable to conclude that physics in particular is a little-explored field. Moreover, modeling, which is identified in the “environmental impact” cluster, is clearly very little covered.

- Focus on implementation techniques
- In order to provide a closer insight into the contributions concerning implementation in Section 3.1.2, an analysis of keyword co-occurrence was carried out on the publications relating to them. The time scale is added to the visualizations to underline the trend over the last few years. All techniques are included, as they have been studied in over 10 publications (Figure 22).

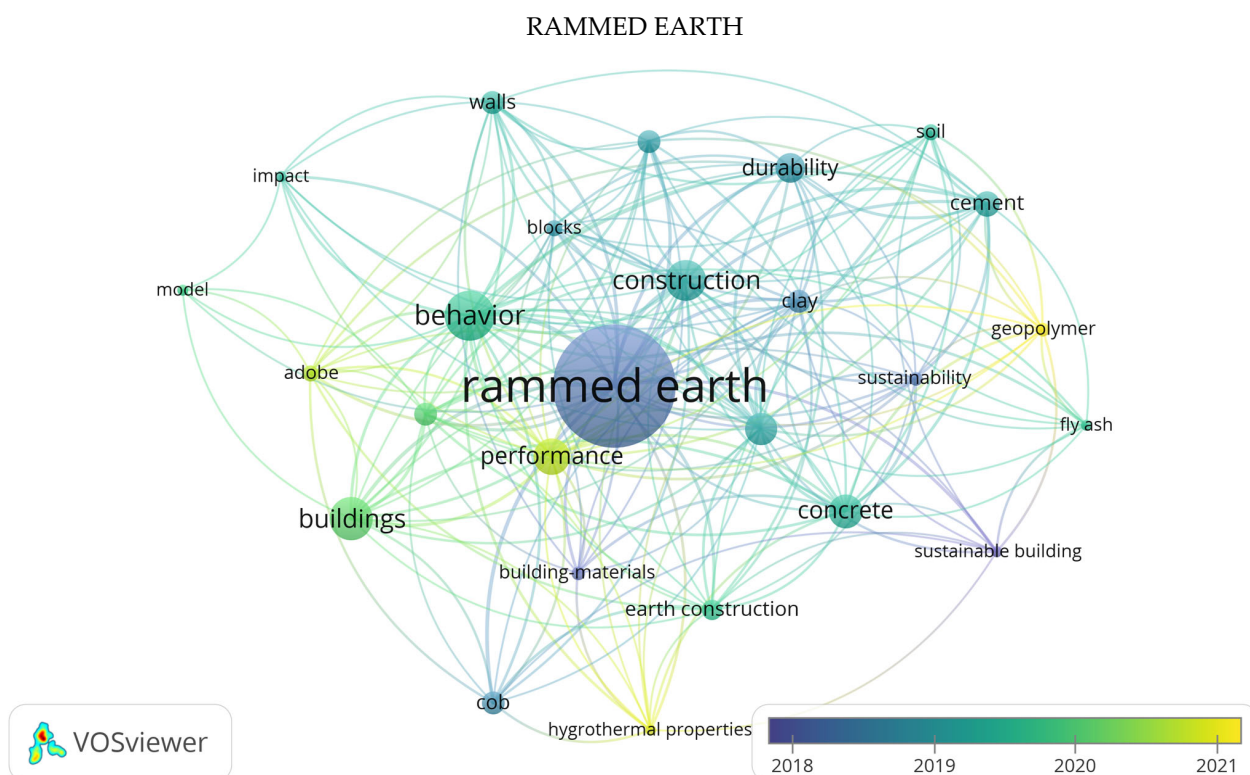


Figure 22. Cont.

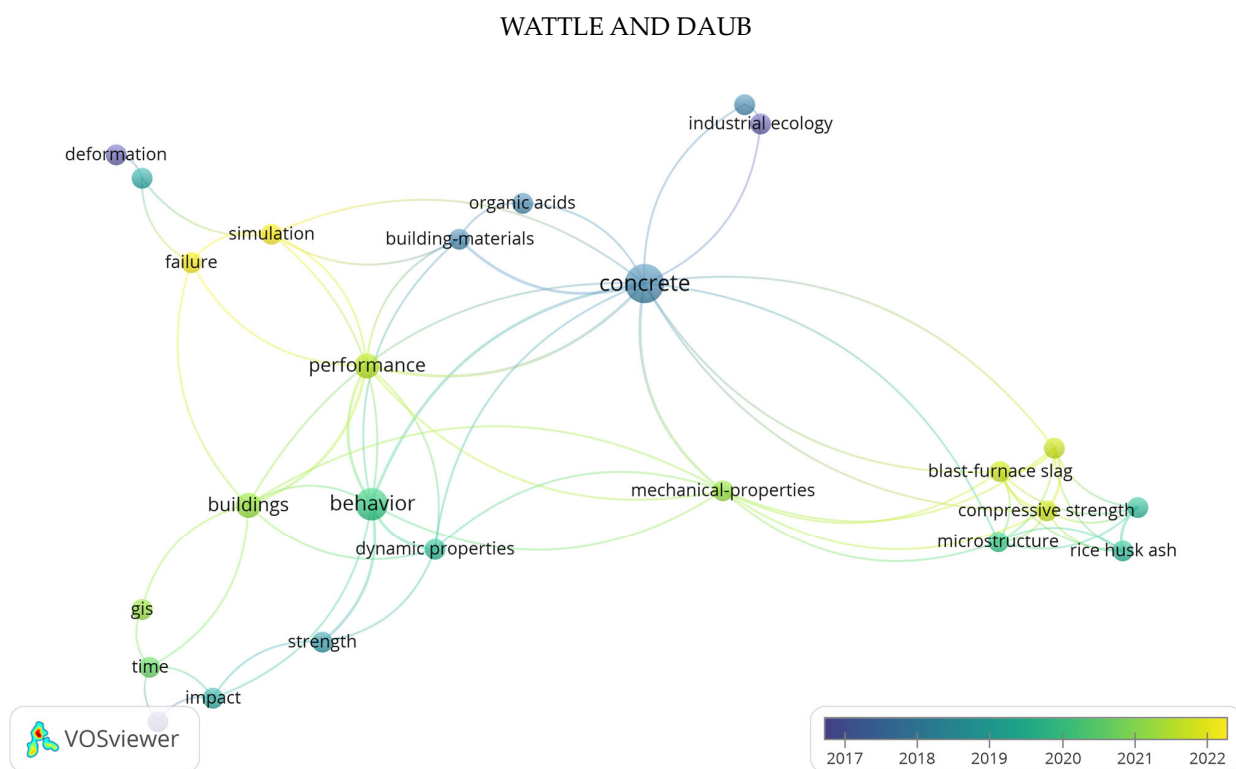
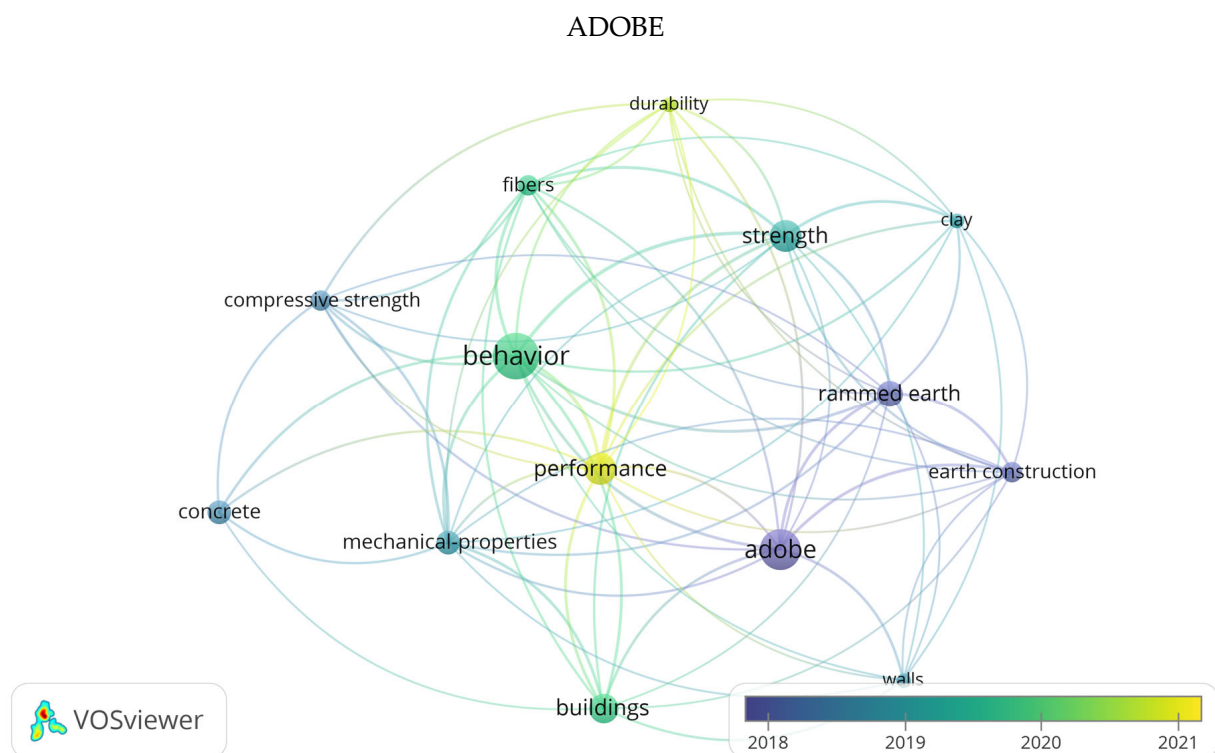


Figure 22. *Cont.*

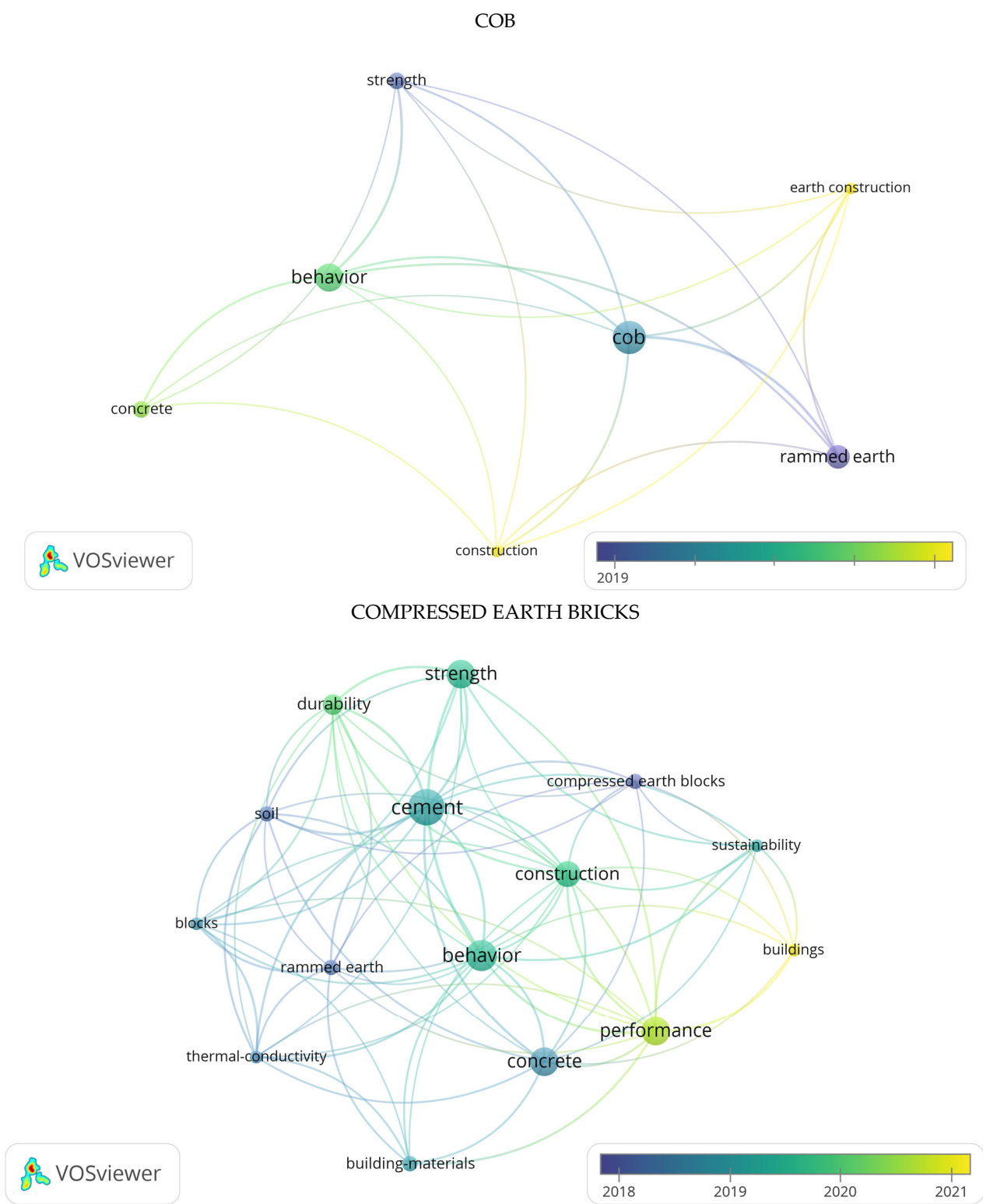


Figure 22. Cont.

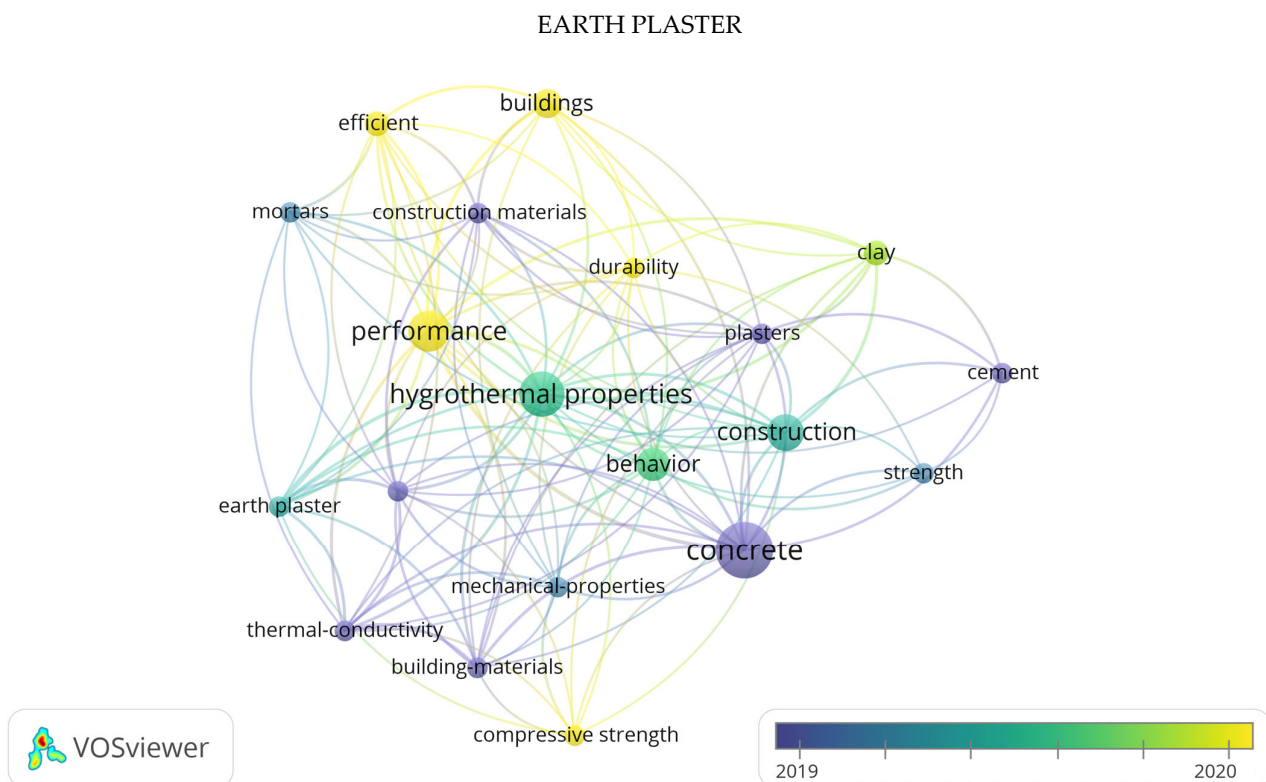


Figure 22. Co-occurrence networks of keywords concerning publications about the most widely studied raw materials in the literature.

In load-bearing techniques such as rammed earth, adobe, cob and compressed earth blocks, terminology related to mechanical properties is logically prevalent. For wattle and daub, the subjects span a broader spectrum, ranging from microstructure to mechanical properties and organic acids. The hygrothermal properties of plasters are clearly targeted by the studies carried out to date. It is interesting to note that the term “cement” appears on many cards. This may appear surprising, but it certainly stems from the systematic comparison of earth materials with conventional ones. The emergence of the terms “fibers” and “rice husk” demonstrates the close link between bio- and geo-based building materials. Identified areas for further exploration to address certain limitations likely include:

- Variability of the raw resource [118,119]: raw earth is a mixture of clay, silt, sand, gravel and pebbles of varying natures and proportions, depending on where it was extracted [120].
- Pre-conceived ideas: earth can suffer from a bad image for economic, political and social reasons [24,60]
- Traditional craftsmanship: as earth is a material used for millennia, the implementation techniques are often the result of real know-how sometimes difficult to reconcile with current techniques and constraints [60,121].
- Life cycle assessment: as earth is a low-embodied carbon construction material [24], life cycle assessment methodology may adequately demonstrate its potential in place of conventional materials.

3.3.3. Potential Emerging Themes

The visualization maps in the sections focusing on bio- and geo-based building materials enable one to appreciate the most frequently addressed themes and, consequently, those that are less explored. To further enhance the analysis, a co-occurrence map of key words corresponding to articles on composite building materials in 2022 has been generated (see Section 2.2). By comparison, this allows the detection of different themes that could potentially contribute to the development of eco-materials (Figure 23).

Logically, topics similar to eco-materials can be found, such as mechanical behavior and performance. Performance is linked in an interesting way to optimization, which was not identified in the case of bio- and geo-based building materials. This suggests it as a first avenue of study.

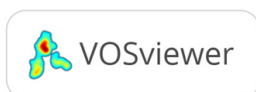
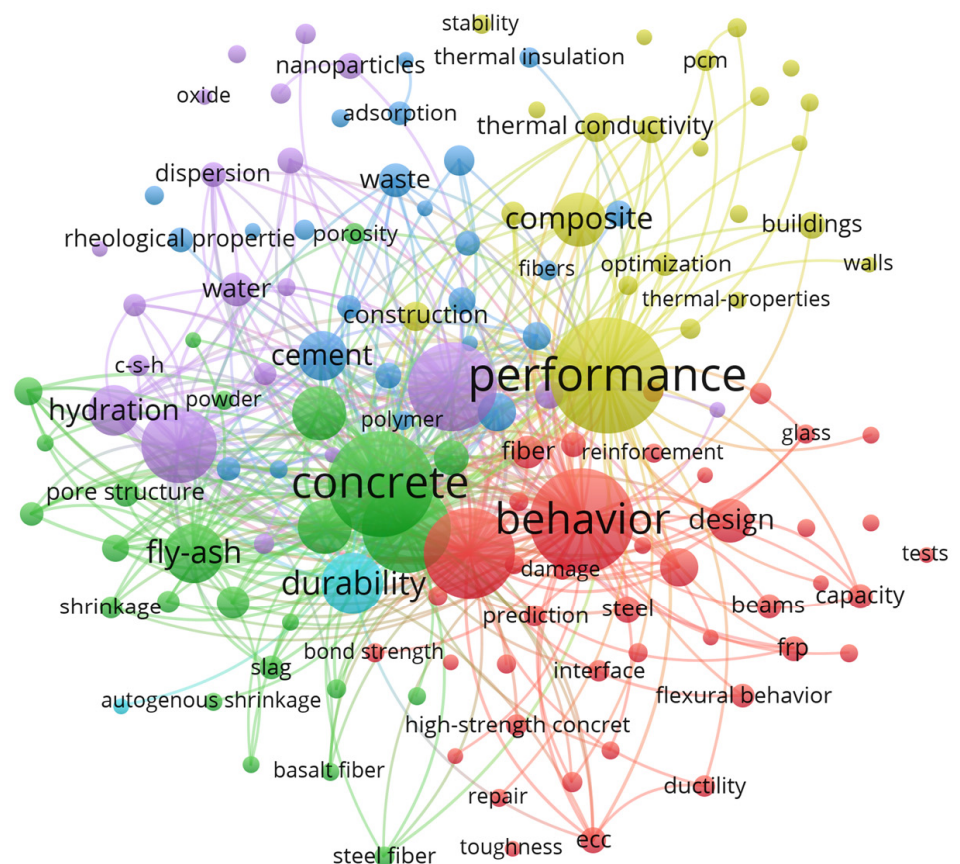


Figure 23. Co-occurrence networks of keywords concerning composite building materials (2022).

In the context of composite building materials, it is worth noting that the study of behavior is linked to modeling with the notion of machine learning. This link was not represented in previous maps, making it another avenue of exploration.

Additionally, emerging themes of interest include durability and microstructure. Sustainability is linked to all of the other clusters, demonstrating its importance in research themes, potentially serving as a third avenue of exploration. Microstructure is widely explored, even down to the nanometric scale according to the themes identified, such as nanoparticles, nanocomposites, nanosheets and graphene. Given its significance in composite materials, it would probably be wise to explore microstructure at a similar scale in bio- and geo-based building materials.

4. Conclusions

In conclusion, a statistical analysis using Web of Science data provided an overview of the disciplines considered: bio- and geo-based building materials. It highlights, in particular, the growing dynamism of research with the increasing number of publications in recent years. The main contributing authors, sources and countries are clearly identified. In terms of volume, the main contributing countries today are China, France and the United States. The authors who contribute the most tend to be European.

In addition, this study relied on a bibliometric network visualization software application. It confirmed the main contributors and also allowed us to appreciate their contribution. Overall, collaborations on a European and global scale remain very limited. A complementary analysis made it possible to identify the major works in each discipline, providing a significant asset for gaining a more academic perspective.

Finally, the combined use of visualization maps and statistical analysis confirmed areas to explore in order to gain visibility in the field of bio- and geo-based building materials. A table summarizes the elements that are particularly useful when starting research work in these areas. It also indicates the main work perspectives proposed following this in-depth analysis (Table 10).

Table 10. Main conclusions of the study.

Topic	Major Authors	Main Subcategories Studied	Research Perspectives
Bio-based building materials	Collet F. Lanos C. Blanchet P. Magniont C. Habert G. Pretot S. Lawrence Mike Langlet T. Maalouf C.	Hemp Wood Straw	Modeling Physics Microstructure Chemical composition Sustainability Energy Resource diversity Structuring the local sector
Earth-based building materials	Aubert J.E. Faria P. Laborel-Préneron A. Magniont C. Humberto V. Niroumand H. Pinto J.F. Beckett C. Zai M.F.M Hamard E. Zai	Rammed earth	Modeling Physics Microstructure Variability of the earth Traditional craftsmanship to modern techniques Pre-conceived ideas on earth

Lastly, recent developments in the IT field offer an additional opportunity. Quantum computers, with increased computing capacities, may be able to address the current challenges of computing time in modeling [122]. Artificial intelligence, notably with digital twins or neural networks, also holds a promising future in advancing scientific knowledge, especially in civil engineering [123–128]. Seizing upon these new tools and the themes highlighted in this article can contribute even further to the development of bio- and geo-sourced materials.

Author Contributions: Conceptualization, S.R.L.; methodology, S.R.L.; software, A.A.-C. and S.R.L.; validation, S.R.L., V.S. and A.A.-C.; formal analysis, S.R.L.; investigation, S.R.L.; resources, S.R.L.; data curation, S.R.L.; writing—original draft preparation, S.R.L.; writing—review and editing, A.A.-C. and S.R.L.; visualization, S.R.L.; supervision, A.A.-C.; project administration, S.R.L.; funding acquisition, S.R.L. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors declare no conflict of interest.

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