A Bibliometric Analysis of Current Status on Biodeterioration of Cultural Heritage during 2018-2022

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A Bibliometric Analysis of Current Status on Biodeterioration of Cultural Heritage during 2018-2022

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Abstract

Biodeterioration occurs through the availability of biotic and abiotic factors favoring the growth of harmful fungi, bacteria and other microorganisms on cultural heritage. Thus, biodeterioration mechanism has raised a global concern since it is commonly detected on cultural heritage buildings located in specific geographical locations such as southern European countries. This study conducts a bibliometric analysis using VOSviewer and OpenRefine for data cleaning by obtaining data from Scopus database of peer-reviewed publications to provide an overview of scientific literatures on biodeterioration. A total of 537 articles were analyzed within the period of 2018 – 2022 to acquire the current status of biodeterioration issue. 537 documents on biodeterioration were published by 1451 organizations from 68 countries.

The co-authorship network map generated the trend of authors in biodeterioration research that identified the most productive author from China and organization from Japan. The co-occurrence network map of the keywords presented the significant interrelations of biodeterioration research field with the development of natural biocides to cope with the colonization of fungi and bacteria on cultural heritage. These results are expected to support the understanding of the intellectual structure of biodeterioration research.

Keywords: Biodeterioration, Cultural heritage, Bibliometric; Microorganisms.

Introduction

Environmental conditions define the characteristics of regulating factors that facilitate the alteration of physical, chemical and biological processes in ecosystem [37]. As of today, the environmental factors have been identified to contribute to the damages of some materials [61] such as parchment and leather artifacts[61], masonry materials[39] and limestone on heritage building[19]. These cultural heritage materials are prone to biotic factors that allow living organisms to grow on surfaces and abiotic factors which refer to high-moisture, precipitations and air pollution[58]. The most common consequence of microorganisms-induced material damages is associated with biodeterioration mechanism[19,32,39,58,61]. The biocolonization that appears on walls or surfaces of heritage buildings has recently gained concerns, particularly related to the greater result of climate change impact such as wind-driven rain[24,39] that accommodates the rise of humidity to cause damage to the building materials.

Cultural heritages located in specific geographical location provide an essential ecosystem for microorganisms that require significant water retention to act as a decomposer as it is well documented by Li and Gu[24] who showed that the building material of cultural heritage possesses physical properties that allow water activity to induce the growth of diverse microorganisms coupled with the availability of mineral nutrients and temperature difference. Microbial colonization occurs prior to biodeterioration when inorganic material surfaces of cultural heritage provide abundant nutrients. In order to expect the presence of biodeterioration, these inorganic materials must be attributed by certain mechanical parameters such as density, porosity, thermal conductivity, compressive strength, humidity, water absorptivity and thermal conductivity[36].

Specifically, microalgae colonization is able to sequester CO_2 as shown by the preliminary study conducted by Devi et al[11] which eventually increases the humidity that magnifies the presence of biodeterioration. Meanwhile, fungi and microalgae showed similar responses when exposed to heat stress: green microalgae shows a wide ranging temperature tolerance of 20°C - 40°C[42] and fungi indicate a far-reaching temperature tolerance range namely 10°C - 35°C[33].

In a particular case, biodeterioration mechanism occurs in inorganic materials. An anaerobic digester with concrete structures also experiences biofilm formation of methanogenic and acetogenic microorganisms corroborating the kinematic of biodeterioration[17]. According to Bersch et al[5], biodeterioration can be identified through the abnormalities of aesthetic and visual that create stains generated by the activities of fungi and other microorganisms, in some cases, this circumstance may indicate environmental pollution in the vicinity of buildings. Since heritage buildings have the function to exhibit historical evidences that link with the rise of urban society, thereby it is essential to particularly sustain the function of its solid structure from pathological manifestation in buildings that contribute to the occurrence of biodeterioration.

On the other hand, Bauer et al[3] have discovered that microbial colonization can be removed from solid structures using bio-cleaning agents such as fungi and cyanobacteria. It shows that particular microorganisms can be benefited to preserve cultural heritage buildings despite its damaging effects corroborated by environmental conditions. Subsequently, the changing climate has the potential to intensify the incidence of microbial colonization on solid structures, thereby it is of great significance to study biodeterioration that occurs in cultural heritage buildings.

Bibliometrics analysis is a proficient tool for conducting a quantitative analysis of publications in particular areas of scientific research based on mathematical methods to establish graphic statistics such as the spatial distribution of publications and most repetitive keywords. Bibliometric analyses are also used to provide citation analysis associated with the relationship between journals, authors and countries through the identification and illustration of research development configurations[35]. This systematic analysis aims for shaping clusters that give rise to key research interest, essential to undergo further investigation[57]. Given its complex nature approach, neutrality and precision, bibliometrics has generated the productivity of particular research in the field of environmental engineering and science such as bioremediation[53], microbiology[18] and emerging contaminant in water[40].

At present, many researchers have laid a great focus on the occurrence of biodeterioration. The objective of this present study is to use a bibliometric approach through the application of a research tool namely VOSviewer visualization software to examine the relevant literature from Scopus database in the research area of biodeterioration within the period of 2018-2022. Besides of that, this study also aims to analyze the current state of the appointed research area, discover the research gaps and chance for advancement and establish references for further research.

Material and Methods

The bibliometric analysis of biodeterioration was performed using Scopus database on the ground of its broad coverage of 80 million documents and 17 million author profiles by 2021[59] which occupy the second wide-ranging database for citation[56]. This narrative method aims to reveal the science maps configurations within the structure of research fields that assists us to categorize interdisciplinary and research flows of specific issues[56]. Meanwhile, Marczewska and Kostrzewski[31] state that bibliometric analysis is used to propose an advanced literature review that promotes visual mapping method to leverage the ground of analysis.

As the powerful method, bibliometric analysis explores the citation linkage that comprises of two approaches: performance analysis (assessment) and science mapping[20,56]. According to Donthu et al[14], performance analysis is in regards with the interpretation of main features of publication, through the analysis of citation, calculating affiliations, authors and regions of publications[13] while science mapping emphasizes the interactions between research components such as branch of knowledge, subject, fields and single or multiple authors that accentuate the observation of a scientific field and setting the boundaries in research areas to decide its perceptive configuration and development[50].

Bibliometric analysis stems from the wide spectrum of scientific results. Scopus as previously introduced, has become one of big scientific databases that enable many researchers to retrieve the immense amount of publications data[14], thus it requires specified software to interpret these data bulks, for instance VOSviewer. Established by van Eck and Waltman[55] from the Centre for Science and Technology Studies at Leiden University, the wide application of VOSviewer software for bibliometric analysis is useful to facilitate the examination of the current status of research and gaps in a research area to generate visual analysis of the existing publications by keywords, year, authors, research institutions etc.[55]

In addition, VOSviewer has the specific purpose for developing and visualizing bibliometric networks in the form of graphical configuration. Subsequently, the graphic can be thoroughly observed by exploring the features and functions, as well as classified in some clusters to generate a clear overview of the network structure. As one of computer based software for quantitative data analysis, this open-access online application is periodically updated and can be downloaded at http://www.vosviewer.com (accessed on 25 January 2022). Therefore, VOSviewer becomes the foremost software tool to apply for this study to generate an improved visualization of networks[28].

The retrieved search results of this study were delivered through tabular delimited text file (CSV) format to be further analyzed through VOSviewer. All data were gathered on 20 January 2022 to authorize the results retrieved for the number of publications and citations by the identification of one keyword namely "Biodeterioration" by limiting time span to the period of 2018-2022. The search result shows 537 publications suited to the preferred criteria. The whole retrieved search results were exported in tabular delimited text file (Comma Separated Value) format established in Microsoft Excel, which contained bibliographical information such as authors, titles, source titles, publications years, author keywords, institutions and abstracts for further interpretations and visualization through the software tool used for bibliometric analysis.

The analysis of the co-authorship relationship and co-ocurrence relationship was executed by VOSviewer by reviewing the number of publications and the annual variation trend of publications contained in CSV format established in Microsoft Excel. The whole prevailed process of bibliometric analysis of the journal is shown in figure 1. Once the graphic configuration appears to be a set of nodes

and edges, then the visualization of networks can be displayed as clusters to provide a thematic view. Each node becomes the symbol of its respective feature and function in a map with an author, a keyword, an article and a journal displayed. Furthermore, each node is characterized by its sphere size to distinguish the degree of centrality and the length of interpolation lines to indicate their relationship. Therefore, two nodes are intensely connected when they are positioned in close proximity. Meanwhile, the bold or sheer links signify the proportionate incidence of co-occurrence and co-citation[75,28].

This research tends to focus on the prominent nodes and conspicuous links in the maps by examining the chosen nodes with its bold links located in each respective cluster differentiated by distinct colors. Afterwards, the same color nodes and links contained in a cluster share identical research components while different clusters contain various units.

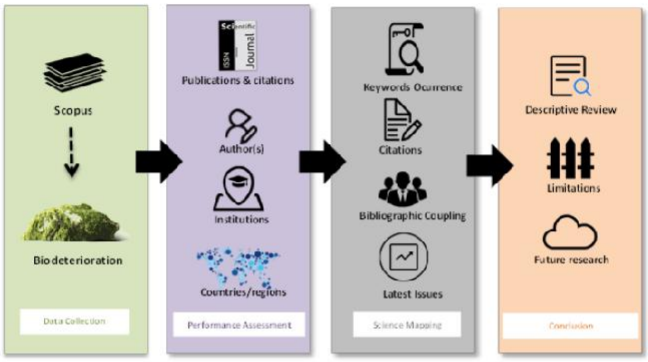

Figure 1: The process of bibliometric analysis[59]

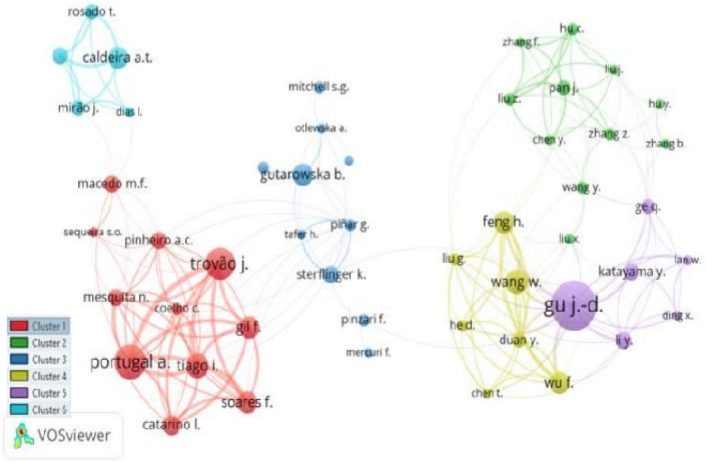

Figure 2: Co-authorship network visualization map with authors' unit analysis

Hence, the clusters help unite the research themes, particularly to enlighten the intellectual structure of biodeterioration research from a variety of views[10]. Besides VOSviewer, this study also uses OpenRefine software to cultivate the whole accurate and incorruptible exported datasets. This data cleaning tool works through the application of specified agglomerative algorithms for eliminating duplications and clarifying ambiguity for the name of authors and research institutions[1]. Afterwards, further data cleaning was purposefully performed through the use of Thesaurus file attached in VOSviewers software.

In order to provide auxiliary analysis for bibliometric data visualization of biodeterioration research within the period of 2018-2022, Tableau and Microsoft Excel™ were chosen to complement the result of VOSviewer software for providing chart or graph. Given its ability to perform efficiency and effectiveness, Tableau generates specifically a suitable feature to organize the fixed data[21] in a simple step through drag and drop the headings of imported data into column and row and to select a chart type[60]. Microsoft Excel™ provides a single platform to accommodate data storage, data analysis and data visualization to combine with simple features of charting techniques.[30]

Results and Discussion

Co-authorship Analysis: The network of co-authorship signifies the aggregate of relationship between authors, organization and countries[2] which shows the position of an author amongst other collaborating authors linked by the amount of publications in similar areas measured by full-counting method to guarantee each co-authorship link possessing the equal weight[38].

Authorship Analysis (Unit of Analysis - Authors): Figure 2 presents the network visualization map that delineates authors' collaboration strength. As can be seen, this configuration result was categorized into six clusters namely red, green, blue, yellow, purple and aqua. In order to obtain an appropriate visualization of co-authorship map, it was purposefully configured to display an author who has a minimum of 4 documents within co-authorship relationship. Then 93 authors were selected. However, the network visualization only established 50 authors.

Through the analysis of co-author research networks on authors for biodeterioration research, Gu J.-D was referred to achieve the highest number of interrelationship between journal, citation and link strength by a record of 20 papers with 219 citations and 71 total link strength. Link strength is defined as an absolute value owned by each link with the likelihood to elevate when the two researchers have merged to co-author; meanwhile total link strength is to delineate the aggregate strength of the links of an item compounded by other items[6]. Gu J.–D located in cluster 5 altogether with six co-authors also showed a strong relationship with one author Liu X in cluster 2, two co-authors in cluster 3 namely Sterflinger K. and Pinzari F and several authors in cluster 4. Furthermore, the top 10 productive authors of biodeterioration research between 2018 and 2022 are shown in table 1.

The number of publications on the biodeterioration in the Scopus showed that biodeterioration research has attained intensifying attention in the last five years. The number of published articles grew from 109 in 2018 to 537 in 2022 with an average annual growth rate of 85.6%. Therefore, the number of scientific research achievements indicated a significant advancement. The steady rise of total publications indicated that there was still a large space for development. It can be predicted that the biodeterioration will become a promising research niche for researchers to be intensely observed especially in the effort to seek for advanced restorative agents[52], or the use of eco-friendly compounds[45] to protect cultural heritage building from biodeterioration in the future.

Authorship Analysis (Unit of Analysis - Organizations): A total of 1451 institutions were involved in the 537 publications related to biodeterioration during 2018–2022. Departamento de Edafoloxía e Química Agrícola, Facultade de Farmacia, Universidade de Santiago de Compostela reported the highest number of publications with 6 articles. However, this study only selected the organization with the greatest total link strength, thus Departamento de Edafoloxía did not appear on the visualization map (Figure 3) due to its total link strength only showing 2.

Furthermore, this organization unit of analysis selected two items for the least number of citations of organizations which resulted 105 organizations to meet the minimum threshold. Therefore, this algorithm calculation performed 16 connected organizations that categorized into three clusters as shown in figure 3: red as cluster 1, green as cluster 2 and blue as cluster 3. Tokyo National Research Institute for Cultural Properties which produced 5 articles, reached the highest total link strengths of 12 altogether with National Research Center for Conservation of China generating 5 articles with 8 of total link strength. Meanwhile, three other different organizations from China have respectively published 4 articles which occupied 0.21% of the total organizations. This trend of publications based on organization performance (documents and total link strengths) is shown in figure 4.

Two upper confident interval for the citation of articles achieved by two Chinese institutions namely Laboratory of Environmental Microbiology and Toxicology, School of Biological Sciences, The University of Hong Kong, China (54) and MOE Key Laboratory of Cell Activities and Stress Adaptations, School of Life Sciences, Lanzhou University (53) indicated that they have established a particular development in the field of biodeterioration. Those publications are respectively identified as following "Microbiome and nitrate removal process by microorganisms on the ancient Preah Vihear temple of

Cambodia revealed by metagenomics and N-15 isotope analyses" and "Fungal diversity and its contribution to the biodeterioration of mural paintings in two 1700-year-old tombs of China".

These two highlighted articles focused on two renowned ancient heritages that become specifically vital to be restored from biodeterioration, as the ancient Preah Vihear temple has caused a territorial conflict between Cambodia and Thailand since almost 60 years ago and possesses an important cultural meaning for both countries[49]. On the other hand, Ma et al[29] inferred that the two 1700-year-old tombs of China hold the new discovery value of archaeological and historical heritages of two dynasties in ancient China.

The number of publications on biodeterioration established by the top 10 organizations presented a fluctional trend in the examined lapse of time (Figure 4). The publications based on organization were dominated by organizations located in East Asian countries, namely Japan, China and Hong Kong. This should reflect the rising concern of these three countries to conserve cultural heritage as their urban identity and linkage with environment[9].

Table 1
Top 10 Authors in Biodeterioration Research during 2018 – 2022

Author	Number of Works	Total Link of Strength
Gu J. –D	20	71
Portugal A.	14	70
Trovão J.	13	67
Tiago I.	10	59
Gil F.	9	55
Catarino L.	8	51
Mesquita N.	7	44
Sterflinger K.	7	12
Ge Q.	6	20
Piñar G.	5	19

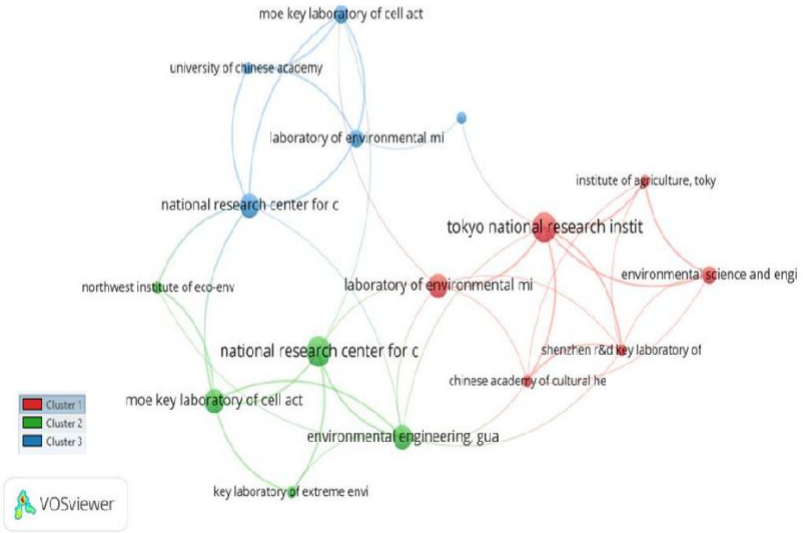

Figure 3: Co-authorship network visualization map with organizations' unit analysis

Figure 4: Trend of Publications by the Top 10 Organizations (Period 2018 – 2022)

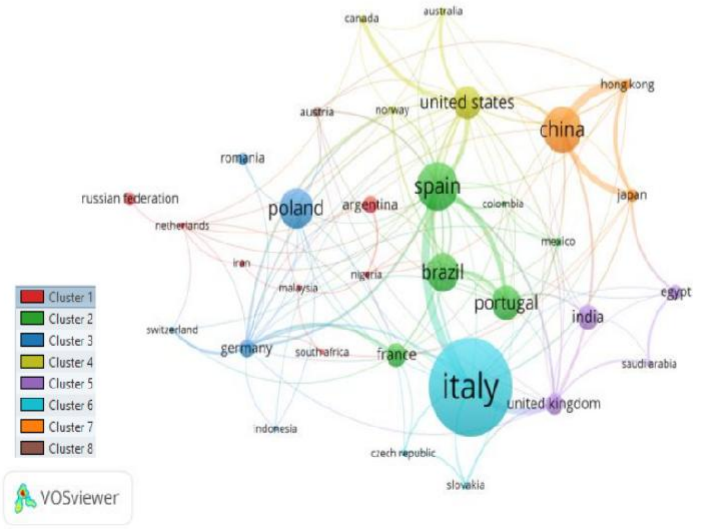

Figure 5: Co-authorship network visualization map with countries' unit analysis

Authorship Analysis (Unit of Analysis - Countries): The 537 records in the Scopus database indicated that 68 countries/territories contributed to the biodeterioration publications. The average productivity of some authors was from Portuguese nationality, yet Italy performed as the most productive country due to its highest number of publications as in figure 5. However, Spain obtained the highest collaboration intensity as it generated 46 of total link strength with 496 citations. In addition, collaborations displayed by the identical linguistic group (green cluster for Spanish-speaking countries and yellow cluster for English-speaking countries) were also manifested. This wide ranging of geographical locations of authors is in accordance with the research done by Sequeira et al[47] who exposed the highest number of participants for fungal biodeterioration research questionnaire from United States, Brazil and United Kingdom.

Figure 6 shows the most productive countries in the research of biodeterioration during the years 2018-2022. The top 10 countries displayed collaborations in biodeterioration publications, ranked by the number of documents with the consideration of total link strength and citations. The top 5 countries were responsible for 55.12% of the total number of publications. The number of publications and citation frequency of Italy were in the top place accounting for 19.9% of the total, indicating that Italy had a relatively high level of influence in the field. This position was followed by Spain with 53 articles and the average cited frequency per paper was 496, which was higher than other developed countries such as US, UK, Germany and France. It can be speculated that the research on biodeterioration has a relatively close association with cultural heritages located in many sites of southern European countries.

As defined by Petti et al[37], Spain had its own explicit legal in regards with the preservation of the structural and settings of historical sites since many historic residences have been replaced with new fangled residential properties. In addition, UNESCO released the World Heritage list in 1972 that aimed to prioritize Italy as the first European country that required concern for cultural heritage protection.

Co-occurrence Analysis: A co-occurrence relationship takes place when one article reveals two units simultaneously[28] which may give the understanding of fundamental configurations of the document belonging to a discipline[23]. Co-occurrence analysis aims to classify keywords into distinct clusters where each cluster is distinguished with various colors[62].

Keyword Occurrence Analysis (Unit of Analysis - All Keywords): According to Liao et al[25], keywords analysis of co-occurrence aims to assist scientific research through the effective disclosure of the elevated dominance research area in the subject field. Based on the result of network visualization (Figure 7), the keywords were distributed into 4 clusters where the main keyword "biodeterioration" is attached to red nodes of cluster 1 with the highest occurrence of 322. Other keywords with a high occurrence were comprised of "biodegradation" (188), "fungi" (142) and "bacteria" (107).

The incidence of co-occurrence reflects the link strength between two keywords. The various keywords are configured in nodes with relationship reflected by the link strength to provide the information of quantitative index. Through algorithm calculation, 98 keywords were chosen amongst the total of 4906 keywords by eliminating the number of occurrences of a keyword to the amount of 11, thus, the node "biodeterioration" showed more obvious lines with "biodegradation" (131),"fungi" (87), "bacteria" (69) and "cultural heritage" (64) as well as "microorganism" (51). These nodes were included into the category of greater number link strength of 50 which suggested the interconnection between biodeterioration and bio-agent of solid structure degradation.

Meanwhile, "biodeterioration" also displayed less obvious link strength with "microbial community" (32), "aspergillus" (29), "colonization" (27), "building material" (24) and "nonhuman" (22). These configurations showed required abiotic and biotic components to enable the appearance of biodeterioration on building material. In addition, Liu et al[26] investigated that *Aspergillus* classified as genus of fungi, had the ability to be a deteriorative agent and commonly occupied a major fraction in the airborne microbial communities which often attributed to the damage of building material. Furthermore, the top 10 highest frequencies and total link strengths of keywords are shown in table 2.

Keyword Occurrence Analysis (Unit of Analysis - Author Keywords): A total of 1669 keywords were set to a minimum number of occurrences of a keyword which was 4 and generated 72 to meet the threshold. Subsequently, the number of occurrences and their total link strength were calculated to select the keywords with the greatest total link strength. "Biodeterioration" appeared to be the most frequent keyword with 268 occurrences and 380 total link strength followed by "fungi" that recorded 61 occurrences and 123 total link strength.

Figure 8 shows a network visualization map that configures one cluster to be frequently linked with other clusters. The largest cluster namely cluster 1 consists of air quality, anti-microbial activity, antifungal activity, antimicrobial, cultural heritage conservation, cultural heritages, essential oils, indoor environments, mural paintings, nanoencapsulation, natural biocides and stone biodeterioration.

The following clusters are cluster 2 with 11 items; meanwhile 3 and 4 respectively consist of 9 items. The remaining clusters consist of less than 9 items. However, the most conspicuous node "biodeterioration" is attached to cluster 7.

Based on the classified cluster shown in figure 8, each cluster demonstrated the authors' focus of research. Cluster 1 showed the use of biocides to remove the microbial colonization on cultural heritage; cluster 2 displayed the most exposed surfaces to biodegradation; cluster 3 provided some environmental factors related to corrosion; cluster 4 discovered the tendency of algae implications to colonize building material; cluster 5 indicated the diversity of microbes and its development; cluster 6 focused on the properties of fungi and its implications; cluster 7 represented the association of biodeterioration and type of fungus; cluster 8 encapsulated the biocolonization on plants and solid surfaces; cluster 9 showed the impact of biodeterioration related to human health and last cluster 10 only displayed the subject of biological aerosol.

In addition, the total 10 clusters showed the interconnection of the course of structure deterioration with its various processes due to microorganisms' activities that required conservation and restoration attempts using different mechanisms.

Figure 6: Productivity Trend of Publications per Country (Period 2018 – 2022)

Table 2
Top 10 Keywords of Biodeterioration Related Publications

Keywords	Frequency	Total Link Strength
Biodeterioration	322	1513
Biodegradation	188	1377
Fungi	142	1075
Bacteria	107	861
Cultural Heritages	90	508
Deterioration	82	658
Biofilm	74	541
Microorganism	67	463
Nonhuman	59	670
Article	57	628

Through the examination of this network visualization, the dominant deteriorative agents can be inferred based on the given link strength with "biodeterioration" whereas "fungi" was positioned as the major cause of biodeterioration due to its highest link strength of 43 with "biodeterioration" followed by "cyanobacteria" (12), "bacteria" (10) and "algae" (5). Through the attempt to investigate the factors influencing the growth of algae, Karima et al[7] added the adequate amount of nitrogen as the determining nutrient to stimulate algae growth.

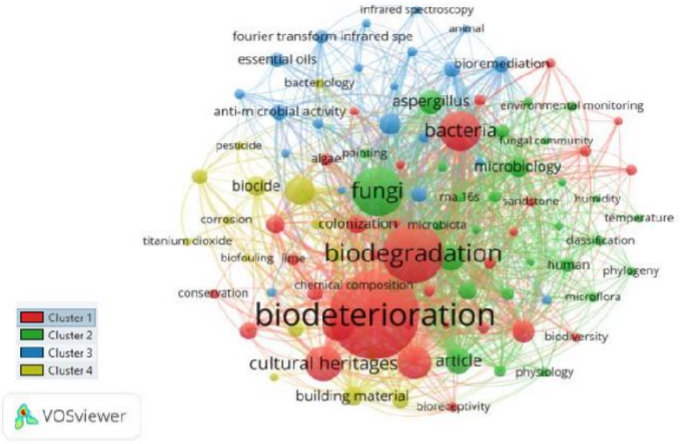

Figure 7: Co-occurrence network visualization map with all keywords

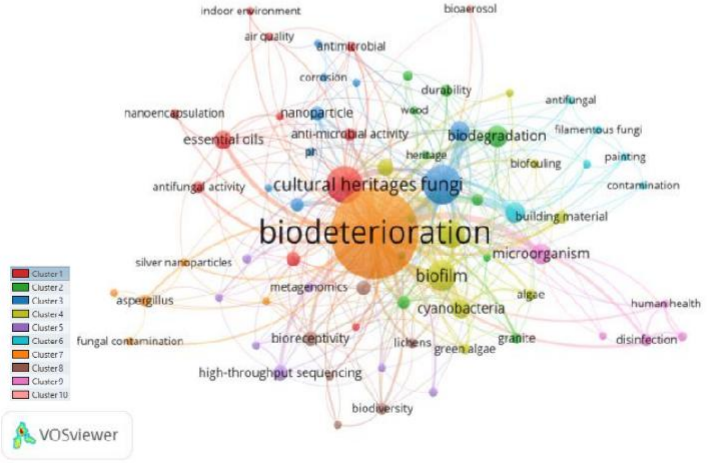

Figure 8: Co-occurrence network visualization map with author keywords' unit analysis

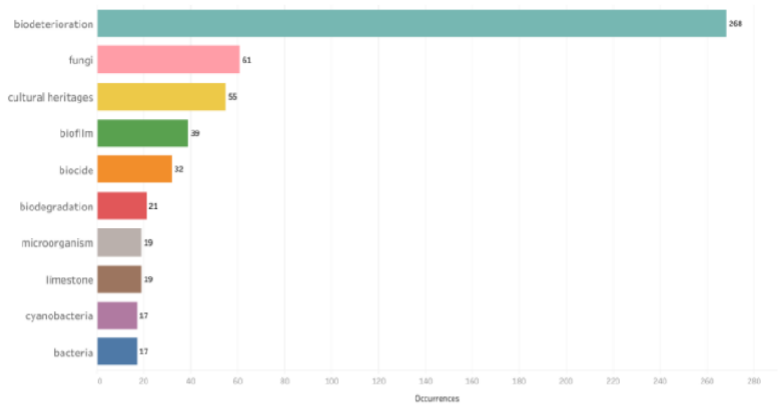

Figure 9: The results of the Co-Occurrences of Author Keywords

On the other hand, this map was also useful to determine the common locations of biodeterioration. Based on the given link strength with the keywords "biodeterioration", the most common locations of biodeterioration settings were: "cultural heritages" (38), "limestone" (14), "building material" and "sandstone" (5). Additionally, figure 9 shows the highest occurrence keywords of author keywords analysis which aimed to delineate the results of the co-occurrences of author keywords, particularly in biodeterioration research.

Keyword Occurrence Analysis (Unit of Analysis - Index Keywords): Based on the research of Nadzar et al[34], index keywords of co-occurrence analysis have the potential to help recognizing the subject area of research. In this analysis, the most dominant cluster was red cluster with 31 items that reflected the highest occurrence and largest total link strength. Of the 31 items in the red cluster, "fungi" became the keyword with the highest occurrence of 113 and total link strength of 865. However, a higher occurrence number does not guarantee a higher value of total link strength as this anomaly happened for the keyword of "biodeterioration" that possessed a higher occurrence number (132), yet it had lower value of total link strength (761) than "fungi".

"Biodeterioration" as the prime keyword did not necessarily associate with other subject fields, while "fungi" may had more probabilities to link with other subject fields such as "chemistry", "animals", "genetics", "alternaria" and "cladosporium". Moreover, the item "biodegradation" showed the highest value of occurrences (177) and total link strength (1191) which surpassed the prime item "biodeterioration". This result might indicate that the keyword "biodegradation" generated more relevant term with other remaining items than the keyword "biodeterioration" within the index keywords analysis. The term "biodegradation" as defined by Sierra-Garcia et al[48] had more pertinent role to explain any process related to chemistry such as hydrocarbon biodegradation using microorganism.

In order to have deeper investigation about index keywords analysis, the network visualization map had been displayed in three clusters as depicted by figure 10 where each cluster portrayed the intellectual structure of the research. Cluster 1 marked by red color established 31 items that translated the subject field of biodeterioration into several components, namely the biodeterioagent such as *Aspergillus*, which caused biodegradation that led to biodeterioration of solid structure and soft materials that required environmental monitoring to observe the growth and development, thus this area needed to explore another subject field namely microbiology to comprehend the microbial diversity.

Meanwhile, cluster 2 represented by green color, consists of 28 items demonstrating the incidence of biodeterioration that happened in several countries such as Italy due to the presence of a number of microorganisms including alga and bacteria supported by some environmental factors. This cluster also pointed out the sequence of microbial colonization on cultural heritages, monument, limestone and sandstone which appeared prior to the occurrence of biodeterioration. Thus, this course needed to be addressed in a serious attempt, for instance historic preservation. Lastly, cluster 3 focused on the attempts to diminish the existence of microbial colonization on building material through the use of chemical material and biocide. However, this effort has been further intensified through the development of natural biocides such as essential oils to replace the usage of antifungal agent or pesticides that may further harm environment.

Regarding the inconsiderable use of pesticides, Sunaryo et al[54] established a controlled study of natural bacterial to provide the inverse ability to eliminate the contamination of chlorpyrifos, a most frequently applied insecticide, from aquatic environment.

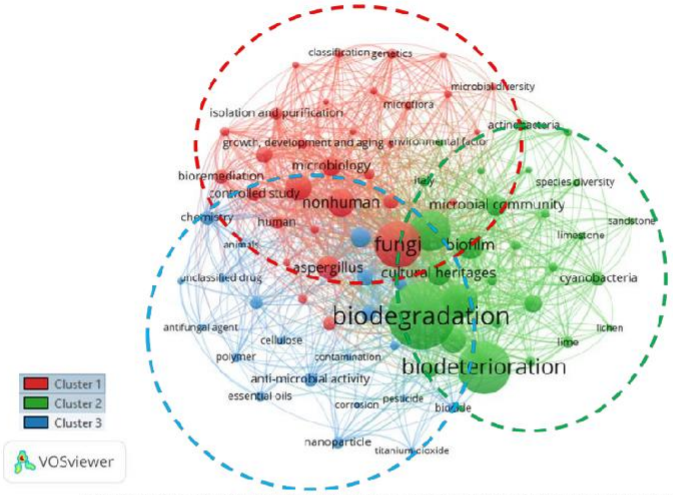

Figure 10: Co-occurrence network visualization map with index keywords' unit analysis

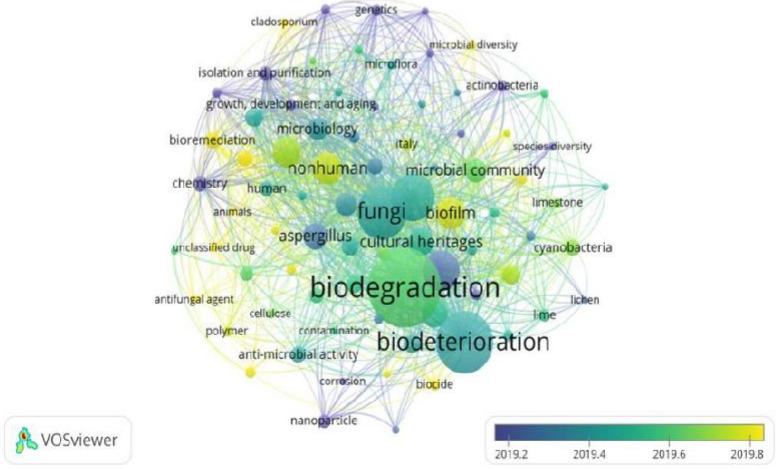

Figure 11: Co-occurrence overlay visualization map with index keywords' unit analysis

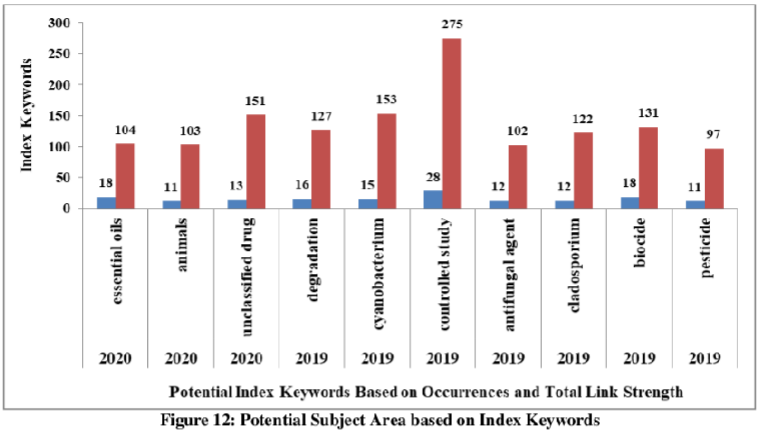

Figure 12: Potential Subject Area based on Index Keywords

Lovasi et al[27] highlighted the serious threat of exposure to chlorpyrifos for human health, particularly after its extensive use for preventing the termite colonization into cellulose based material to cause building deterioration[15]. In addition, the bibliographic data was also configured in an overlay visualization to indicate the latest subject field of biodeterioration as shown in figure 11 marked by yellow cluster. Besides revealing the latest subject field, this index keywords map could identify the potential subject field of biodeterioration.

A number of potential subject areas of biodeterioration research can be seen in figure 12 graded on the latest years' publications. A few of keywords had the potential to be further explored are "cyanobacterium", "essential oils" and "biocide", especially when these three keywords appeared together in the research of biodeterioration of cultural heritage. According to the research of Soares[51] cyanobacterium had become the frequent issue to consider due to its capability for colonizing cultural heritage which thereby required a novel approach for protecting the cultural heritage by reducing the use of chemical biocides that may further harm the environment and human health.

Several researches confirm the importance of establishing the attempt for cultural heritage conservation through use of natural plant based biocides, such as essential oils that showed confident result to obliterate fungi and bacteria in an indoor area and artistic mural without reducing the quality of environment and human health[12]. In order to address the negative impact of chemical biocides, the development of polymer based biocides built in essential oils modified nanocomposites has been intensively established to perform anti-microbial activity against the biofilm formation of gram negative bacterium *Escherichia coli*[8,46]. The heterotroph bacteria such as *E.coli* are easily attached to the surface and provide the ability to generate biofilm formation which commonly generates contamination for drinking water sources[1]. A study of Rohmah et al[44] delineated the high number of *Ecoli* measured from several points of groundwater wells in the south of Jakarta and were not strongly attributed to the distance of the well to the septic tank or the depth of the well, which thereby allows further study to investigate the presence of biofilm formation within ground water wells and the attempt for biofilm removal. Biofilm is commonly built on a surface by bacteria facilitating an aggregation of microorganism cells to release a restraint of adhesive derived carbohydrate which eventually generates resistance layer to environmental factors[15].

Conclusion

The bibliometric analysis of this study stemmed from 537 related articles on biodeterioration which retrieved within the period of 2018 to 2022. Based on the investigation throughout the articles using VOSviewer and OpenRefine application software, it can be concluded that the research topic "biodeterioration" has been dominantly occupied by authors from countries with cultural heritage influence within the last five years. The articles published within 2018 until 2022 generated the growth rate of 85.6%. The country with its highest number of articles was Italy (107) although Spain obtained the highest collaboration intensity as it generated 46 of total link strength with 496 citations. Meanwhile, Tokyo National Research Institute for Cultural Properties became the institution with the largest number of published articles (5) and 12 of total link strength.

Based on the co-occurrence analysis of high-frequency keywords, "biodeterioration" research was relatively peripheral. Fungi and bacteria were recorded as the most relevant deteriorative agents to cause biodeterioration. The

most highly cited publications were conducted on two renowned ancient heritages namely the ancient temple and tombs that became specifically vital to be restored from fungi and bacteria. Biodeterioration and biodegradation were two field researches that adjacently appeared in the result of bibliometric analysis. However, biodegradation showed more affiliation (overlapping subject) with other subject area than biodeterioration as these two research areas are interdisciplinary related to microbiology.

Since microbial induced deterioration occupies a significant area in microbiology field, therefore a number of pertinent researches in the widening area of microorganism are entitled to be slightly portrayed in this study. In the course of biodeterioration where microorganism such as bacteria becomes the ground of limestone - built cultural heritage to decay, three selected bacteria of their origins were conversely benefited in the research of Rinanti[41] to penetrate the limestone formation as reservoir rock for oil content extraction. However, Bücker et al[7] have discovered that the biofuel containers were at risk of biodeterioration by fungi colonization which delineated the tendency of microorganism to grow in a particular medium of abundant carbon and energy source. The inclination of microorganism to interact with hydrocarbon provides the well-studied area of "bioremediation", one of the keywords that appears as part of yellow nodes in figure 11.

A research of Rinanti and Nainggolan[43] encapsulated that the number of growing bacteria as bioremediation agent was increasing along with the rise of reduction amount of petroleum residue.

In the last few years, publications on biodeterioration have rapidly increased confirming that international policies and academic research have recognized that biodeterioration occurs in cultural heritage as a definite destruction mechanism takes place in cultural heritage and lime stone – built structure aggravated by climate change and other environmental conditions that need to be promptly addressed. Despite its challenge to conserve cultural heritage from biodeterioration, the results of this study show the evolving approaches to cope with microorganisms - colonized materials.

Some further studies are auspiciously to be carried out in the field research of "cyanobacterium", "essential oil" and "biocide", applying the natural plant-based biocide for removing fungi and bacteria in cultural heritage; observing essential oils as a novel approach to protect cultural heritage from biodeterioration. Moreover, the research of natural biocides developed in a controlled study also shows a promising niche for research in the future.

Bibliometric network analysis suggests a comprehensive statistical approach to capture the main aspects contributing to the components of biodeterioration issue by examining the interactions between the authors, organisations, countries and keywords. The main value of this proposed method offers a flexibility to interpret the result of configuration retrieved from a bulk of literature database. Nevertheless, it must be pointed out that this study also faces some limitation as the source of data is confined to consider only one single database of peer-reviewed journals (Scopus database). Besides, the cleaning process of redundancy keywords requires a thoroughness attempt that causes time – consuming and leads to subjectivity.

Ultimately, biodeterioration occurs in cultural heritage and will require a further investigation to generate more environmentally suitable approaches to interfere the growth of the damaging microorganisms on solid structures without giving additional harmful impacts on environmental and human health.

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