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A SYSTEMATIC REVIEW AND ANALYSIS OF 3D PRINTED BUILDING ENVELOPES INSPIRED BY NATURE

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Abstract

In recent years, 3D printing (3DP), a type of additive manufacturing process, has undergone rapid transformation. A systematic approach to knowledge transfer from biological concepts to technical applications has made significant progress in the last 10 years, and bio-derived developments are frequently described as sustainable. However, it should be noted that research into the application of bio-inspired geometry in 3D printed building envelopes (3DPBE) is still in its early stages. The goal of this paper is to identify ongoing research trends and current gaps in nature-inspired 3DPBE, through a systematic literature review. The objective of this study is to investigate and synthesise domain knowledge, as well as to identify the current trends and gaps in nature-inspired patterns and their application in 3DPBE. A three-stage methodology was used to identify research gaps, current trends, and future directions in 3DPBE inspired by nature. Scopus was used as a literature search database, VOS Viewer and R-Studio Bibliometrix software tools were used for quantitative analysis and qualitative analysis was carried out by systematic review. The current research trends and gaps in 3DPBE's were identified through R-Studio Bibliometric analysis and through a systematic review the future directions are proposed as follows: A multi-scale approach to design optimisation in the future of 3D printing which will lead to organic streamlined structures with 3D printed nature-inspired patterns in some cases will open a slew of new possibilities, application of eco-friendly materials, life cycle assessment and cost factors. The main contribution of this study is to synthesise the 3DPBE with nature-inspired geometry and expose the insufficiency of literature in this area.

Keywords: 3D printing, Additive manufacturing, Bibliometric analysis, Bio-inspired, Biomimicry, Building envelope, Systematic review.

1. Introduction

Nature inspiration is a valuable resource for architectural design andartistic styles, which formulates the investigation of nature, its formation, order, process, and aspects to replicate or seek ideas from, to address issues of mankind [1]. "Biomimicry is a practice that learns from and mimics the strategies found in nature to solve human design challenges and find hope" [2].

The building envelope is regarded as a critical element for achieving indoor comfort and improving the quality of a building's inner atmosphere. Despite the great potential of biomimicry applications, a technique that explains how to integrate biomimicry and digital design to regulate the cause on the environs, particularly the thermal behaviour of the building's envelope, is needed [3]. 3D printing (3DP) offers green building technology, due to its less material usage, it eliminates a significant amount of CO2 emission and energy utilisation compared with conventional building techniques [4].

This review focuses on 3DPBEs and analyses how inspiration drawn from nature can enhance the efficacy of the building envelope. The majority of research is focused on the structural strength of the materials [5]. However, in this domain, a systematic study to integrate sustainability features is quite lacking [6]. Various review articles on bio-inspired 3DP were identified in this systematic review. Even though their contributions are significant, very few of the earlier reviews concentrated on viability factors or bio-inspired pattern applications in 3DP construction. The main goal of this study is to ascertain the current research trends and gaps in nature-inspired 3DPBEs, with a systematic review.

2. Methodology

This study employs a "mixed-review method" to take advantage of the positive aspects and reduce the negative aspects of both qualitative and quantitative methods [7]. The methodology followed here, consists of a quantitative assessment through bibliometric analysis and a qualitative assessment with a systematic review, allowing it to remove biased conclusions and prejudiced interpretation. The different stages of the study are shown in Fig. 1.

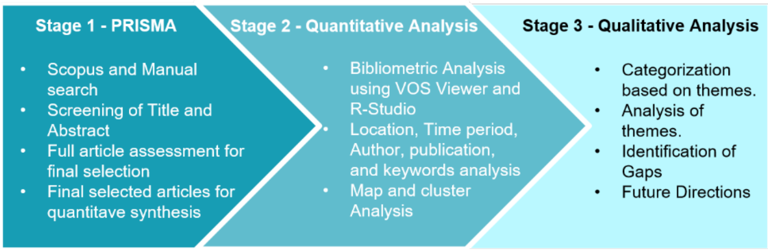

Fig. 1. Methodological stages of study.

2.1. Stage 1 - Systematic review with PRISMA

A systematic review's two main strengths are its transparency, which allows other researchers to replicate it, and synthesises present research on a conferred subject area. A systematic review communicates known and unknown information on a subject area and proposes suggestions for future research [8].

Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines were followed to carry out the systematic review [9], and Scopus was used to search the articles. The reason for selecting Scopus was a relatively large volume of articles available in the construction and architecture research compared to Web of Science, Science Direct, DOAJ, Google Scholar, JSTOR, etc. The authors used a chiselled search that had seven 3DP terms, three components related, and three aid related as shown in Table 1. Articles matched at least a term in the article title, abstract, or keywords are extracted.

Table 1. Systematic review literature search criteria.

Category	Search text
3D Printing	3D Print*, 3d Print*, Additive Manufacturing, Rapid proto*, 3DCP, 3DPC, 3DP*
Building Envelope	Building Envelope, façade, external wall
Nature Inspired	Bio*, Nature inspir*, sustain*

Before the screening, duplicate entries were identified and removed. In the next stage, the authors employed a three-step screening process constituting pre-defined criteria for article exclusion (Fig. 2). The criteria of exclusions are: (1) all articles not related to construction; (2) all materials not related to construction; (3) 3DP methods of non-material extrusion; and (4) the articles in which 3DP printing is not the core subject area.

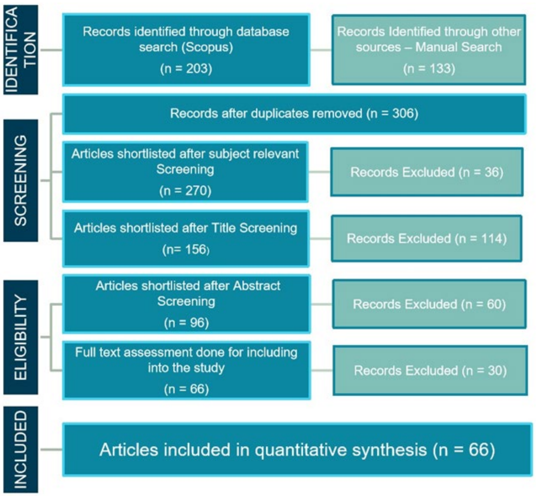

Fig. 2. Systematic review screening process as per PRISMA guidelines.

2.2. Stage 2 - Quantitative analysis

In this stage of quantitative analysis, statistical data of the final short-listed papers are collected to understand the bibliometric variables such as keyword co-occurrence, co-authorship, most cited authors, most cited articles, country, or origin of the articles, etc. The short-listed papers contained documents from Journals, conference papers, and review papers. The quantitative analysis was performed with bibliometric analysis using VOS viewer and R-Studio Bibliometrix tools.

2.3. Stage 3 - Qualitative analysis

In this stage, themes were identified, and the data were synthesised to determine the current trends in 3DPBE research. In line with the identified themes, a categorisation was formed based on the themes relevant to the topic, and the percentage of articles available under each theme is mentioned in the pie chart. Out of 66 articles used in the qualitative analysis around 48% of articles are related to 3DP and 3DCP. Only 15% of articles are related to biomimicry and infill patterns which are more pertinent to the topic.

2. Results and Findings

2.1. Quantitative analysis

The authors short-listed 66 papers from stage 1 of screening, and they were analysed to determine the characteristics of the literature. Owing to a negligible number of articles earlier in the year 2011, the limitation in the year range was set during the search process in Scopus, which resulted in papers from 2011 to 2021.

2.1.1. Bibliometric analysis

A bibliometric analysis was carried out to understand the field and research trend in 3DPBEs. VOS viewer and R-Studio Bibliometrix software were employed for bibliometric analysis. Although there is various software like CiteSpace and CitNet Explorer, etc. that can be used for bibliometric analysis, the authors have chosen the R-Studio Bibliometrix tool due to its dual advantage of analysing and mapping bibliographic data at the same time [10]. VOS viewer tool was used to produce distance-based maps through which keyword co-occurrence, bibliographic coupling, etc., are visualised. It was also majorly used in much earlier construction-related literature review research [11]. As such, research emphases in 3DPBE are analysed and identified using VOS viewer and R-Studio Bibliometrix, which forms a basis for the qualitative analysis in Stage 3.

2.1.1.1. Time series analysis

Figure 3 shows the number of 3DP construction research articles published from 2011 to 2021. From the graph, it is understood that articles in this field were limited between 2011 to 2016 and there were no articles published in any given year before 2012. Research on 3DPBE began a noticeable upward trend in 2017, with a fall in 2018 and steady growth during the last 3 years.

2.1.1.2. Location analysis

Fig. 4 shows the country-wise percentage (first author country) of publications related to 3DPBEs. The highest number of publications which contributes to around 14% was from the USA, Italy stands second with 11% and Australia stands third with 10%.

The relationship between the countries is shown with the VOS viewer map in Fig. 5. In the location analysis, there are three crucial elements: circle size (frequency), colours (relationship), and lines (co-occurrences). These three elements are seen on the map with the country represented as circles, and the relationship with the countries is indicated with colours. The colour and the distance between the two circles indicate the co-publication factor. The lines connecting the circles indicate the co-publication relationships between the countries. The thicker the line, the more co-publications between the countries. In this location analysis, the cluster sizes are set to four papers. From Fig. 5 it can be understood that the USA, Australia, and Italy are the top three countries with more publications in this field. Further, Italy, Netherland, and Portugal with thicker lines indicate more co-publications between these countries.

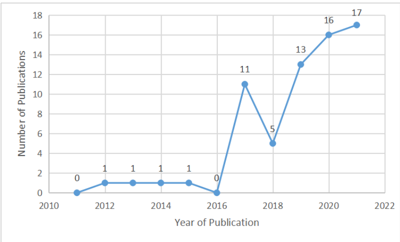

Fig. 3. Annual trend of 3DPBE publications.

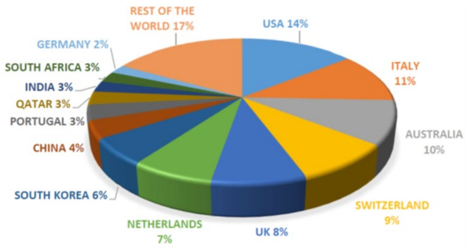

Fig. 4. Country-wise % of publication on 3DPBE.

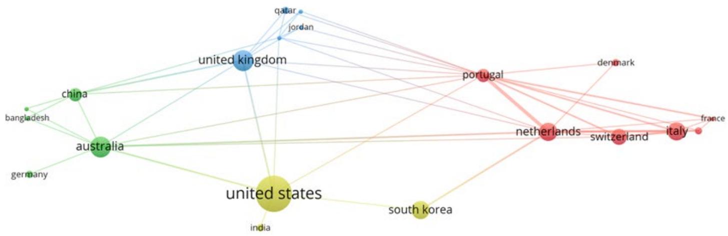

Fig. 5. Map of countries that produced most articles related to 3DPBE.

2.1.1.3. Publication analysis

The Scopus search has retrieved 203 articles containing 107 research papers, 56 conference articles, 29 review articles, 7 book chapters, and 4 conference reviews. The articles cover 9 academic fields, which include engineering (40%), materials science (19%), computer science (17%), energy (7%), environmental science (5%), and physics & astronomy (4%). Figure 6 shows the percentage distribution of the articles subject-wise in a form of a pie chart.

In terms of the publisher, four of the top five producing journals are from the leading publisher Elsevier. Among the four, the Automation in Construction journal was topped with five publications, followed by Additive manufacturing, Buildings, and the Journal of Building Engineering four publications each. Cement and Concrete Composites, Journal of Façade Design and Engineering and Sustainability (Switzerland) stands third with three publications each. The list of

20 most relevant Journal sources for 3DPBE is shown in Fig. 7. The Automation in Construction has the highest citation of 137.

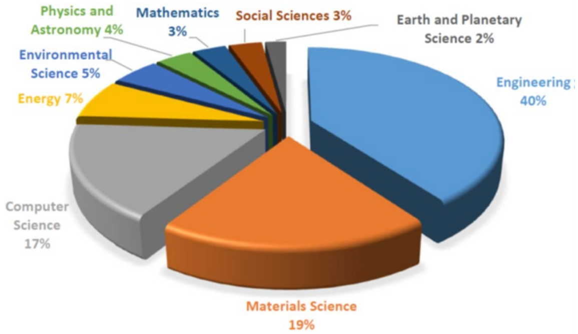

Fig. 6. Subject-wise article distribution percentage.

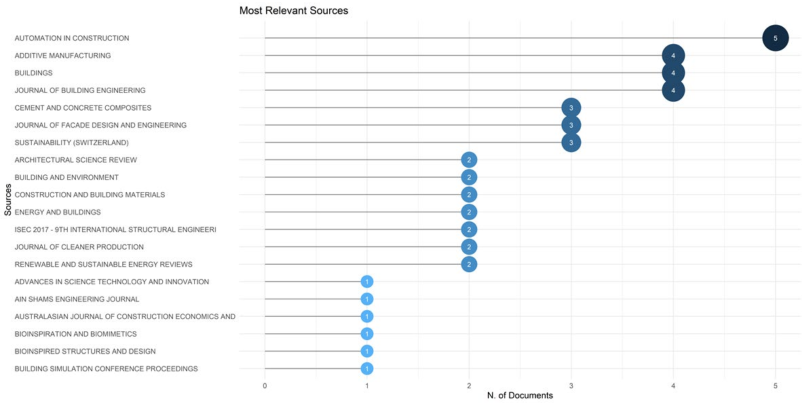

Fig. 7. Journal-wise number of articles related to 3DPBE.

2.1.1.4. Keyword co-occurrence analysis

Keyword co-occurrence analysis is to identify the keywords which represent the knowledge areas found in research articles. The keywords indicate the extent of the research field and indicate the links within the subject area of the research. The network map from R-Studio shown in Fig. 8 reflects the cluster of themes in 3DPBE. This kind of map was presented in some earlier studies as a keywords map [12].

During the process of creating this science mapping, the "co-occurrence" analysis and author keywords check box need to be selected and the occurrence threshold was set to 2 which resulted in generating 115 keywords out of 723. The resulting map (Fig. 8) contained three clusters highlighted with different colours. These three clusters with each representing a domain connected based on the relevance in concept.

Cluster one "Red" (Intelligent buildings, life cycle assessment (LCA), built environment, sustainable development, carbon footprint, environmental impact, etc.). This cluster was formed in relation to the environment which represents a strong focus on environmental sustainability and LCA. These topics are trending in the recent few years [13-15]. Cluster two is “Green” (architectural design, structural and computational design, building construction, building performance simulations, etc.). The 3D design, modelling, and computational performance simulations were studied and their implementation in building construction is discussed [16, 17]. Cluster three “Blue” (3D printing, building envelopes, concretes, cement, thermal performance, energy conservation, biomimetics, etc.). The main concepts of 3DP and building energy systems were the focus of this cluster and the researchers were digging to find the optimum performance of 3DPBEs [18-20]. Figure 9 shows the keywords co-occurrence year-wise generated through VOS viewer indicating the growth of keywords co-occurrence related to the topic since 2017.

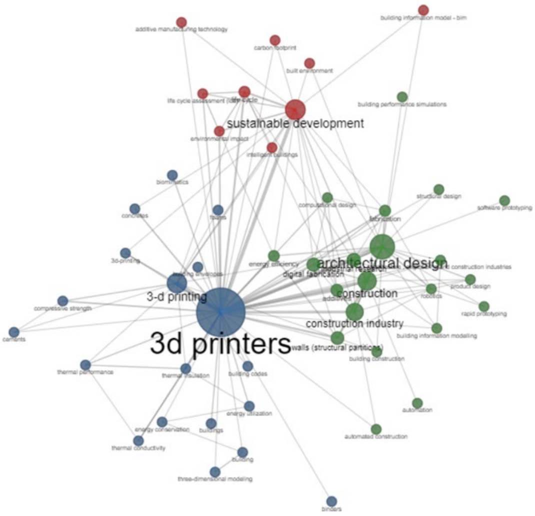

Fig. 8. Scientific analysis of author keywords co-occurrence in 3DPBE.

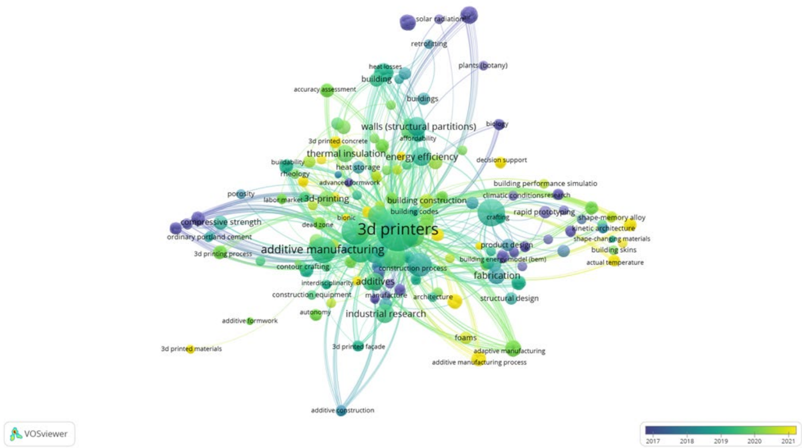

Fig. 9. Scientific mapping of year-wise keyword co-occurrence.

2.2. Qualitative analysis

In stage 3, qualitative analysis was carried out using the identification of core themes to understand the recent trends in 3DPBE research. These themes were categorised based on the research trends and are represented in Fig. 10. The final screened 66 papers out of 336 were taken for qualitative analysis and the period taken was between 2011 to 2021. These articles were carefully selected based on full-text analysis. While selecting the themes it was also considered that they had worthy contents and research outcomes applicable to this review study.

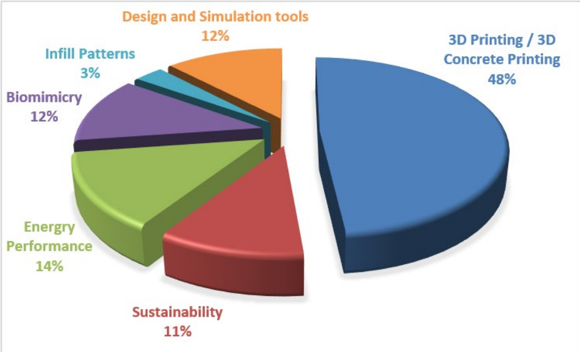

Fig. 10. Categorisation of literature based on themes with the percentage.

2.2.1. 3D printing / 3D concrete printing

3D printing technologies that are currently available for large-scale printing can be categorised as gantry-based, robotic-arm-based, or swarm-based. Among these Gantry-based solutions did a good job of bringing the concept of 3DP at a large scale to life, but still, they suffer several drawbacks such as limitations in the size of printing, transportation of gantry system, printing cantilever structures, etc. Swarm-based printing appears promising in terms of approaching inaccessible construction sites, but they are still too abstract at this point. Looking at the work-flow process and the higher adaptability, playability, and versatility, robotic-arm solutions have a lot of potentials to drive forward the future of large-scale 3DP.

The most important challenge is to make a robotic arm that can work smarter and intelligently integrate the digital and fabrication technology while also determining the best material properties in the best possible environment [21]. 3DP with cement-based materials has opened the door for complex façade construction at low cost and time [19]. Designers are forced to choose lower-cost amid complex designs, necessitating them to produce simple and linear walls. However, the present state-of-the-art 3DP has the flexibility of creating complex geometries that were previously impossible to achieve. Future research may look into this opportunity, not only in terms of an aesthetic standpoint, but also from the viewpoint of structural, thermal, and acoustic performance [21].

2.2.2. Sustainability

Many researchers were concerned about the long-term benefits of 3DPBE. Mohammed et al. [15] used cradle-to-gate life cycle assessment (LCA) to examine the environmental impact of 3DCP compared to traditional construction by studying four case scenarios. They are Concrete construction, 3DCP, 3DCP with reinforcement, and 3DCP with lightweight concrete. In each of the four scenarios, the LCA was performed on an external load-bearing wall of size 1 sq. m. When compared to traditional construction methods, the results of the study have revealed that 3DCP has reduced the environmental effects significantly due to a reduction in concrete material usage, elimination of steel reinforcement, and usage of fly ash. The main goal of the study by Speck et al. [22] was to rationalise and improve bio-derived development, including their sustainability, by considering three main aspects such as descriptive, normative, and emotional aspects.

2.2.3. Energy performance

The components of the building must be designed to attain the best thermal and energy performance based on climatic conditions. This can be accomplished by including void spaces or insulation between the layers of the building envelope in most construction techniques. Architects can design the infill patterns with voids that meet both structural and thermal requirements thanks to the flexibility that 3D printing provides. Alkhalidi and Hatuqay [23] conducted a numerical study to better understand the relationship between 3DP concrete thickness and voids (Fig. 11), which is an important aspect of designing 3DP envelopes that meets the structural requirements. Researchers suggested applying void-filling materials rather than adding layers of insulation if the void configuration failed to attain the requisite thermal resistance. To achieve the desired U-value, insulation materials with specific thermal properties can be filled into these voids.

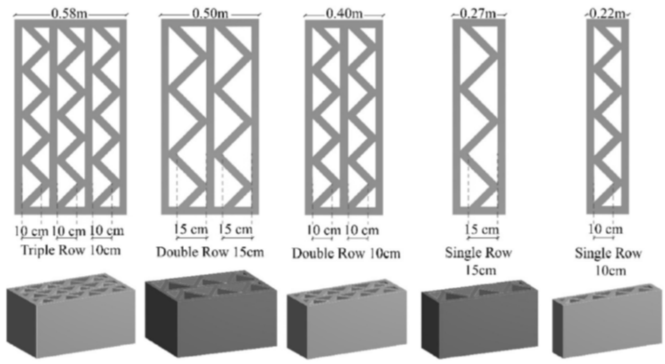

Fig. 11. Various wall configurations show the thickness and cavities [23].

He et al. [24], created a modular building with an integrated vertical greenery system using the 3D printed Vertical Green Wall (3D-VtGW). Their study results indicated that the 3D-VtGW wall system reduces the surface temperature of the exterior wall during the summer season. Mohammed et al. [15], formulated a high-strength, lightweight concrete appropriate for 3DCP which has an improved thermal insulation property thereby lowering the energy usage throughout the concrete structure's life cycle. Suntharalingam et al. [25], in their study emphasised the 3DCP buildings' thermal comfort and energy performance which evaluated 34 wall configurations. Their study established a noticeable relationship between air cavities to the energy performance of 3DCP building envelopes with the inclusion of insulation material.

2.2.4. Biomimicry

Biology is a great source of inspiration for climate-responsive building envelopes and can provide tried-and-true solutions. Plant leaves already have several useful thermal regulation mechanisms in place to keep or release heat as needed. A more focused search for new thermoregulation mechanisms in biology is likely to yield a slew of solutions that can be applied to building envelopes. Furthermore, we should take advantage of new additive manufacturing techniques to mimic biology's complex and fascinating structures [26]. Speck et al. [22] found in a study that there is a need for a system that describes the history of the development of biology and technology-derived solutions as precisely as possible.

In "reverse biomimetics," a biomimetic product development benefits the designer and engineers and natural scientists. The shape of a cellular structure of wood, beehive honeycomb, and spongy bone (Fig. 12) are just a few examples of cellular, porous structures found in nature [27]. The application of these structures in 3DP is widely studied, and they are referred to as lattice structures.

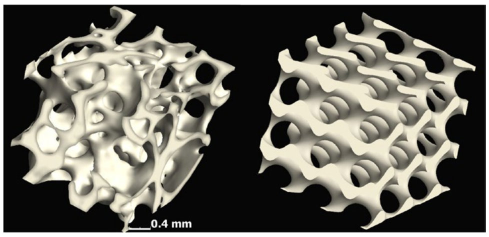

Fig. 12. Cellular structures - trabecular bone and gyroid lattice structure [4].

2.2.5. Infill patterns

Infill patterns refer to the interior support structure printed in a 3D printed object. These patterns will be created in a specific design and scale based on the size of the object. The slicing software is usually in charge of the infill settings, which can affect the strength, material usage (weight), and print time. Examples of 2D infill patterns are regular grid, rectilinear, triangular patterns, and hexagons as shown in Fig. 13.

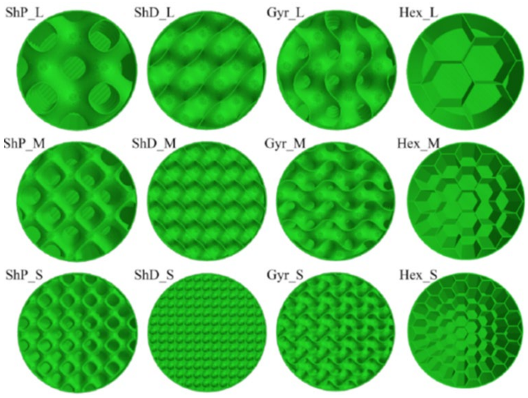

Fig. 13. 3D and 2D infill (left to right): Schwarz p, Schwarz d, gyroid, and hexagon; and sizes (top to bottom): large, medium, and small [28].

The 3D patterns were chosen from a group of triply periodic minimal surfaces (TPMS). Some biological structures in nature, block copolymers, and electrostatic equipotential surfaces in crystals are examples of TPMS in the real world. Most TPMS forms, according to Han et al. [28], exist as a transition between two phases. A gyroid, as well as Schwarz D and Schwarz P, were chosen as 3D infill patterns (Fig. 13). Qin et al. [29] recently investigated the performance of a pristine gyroid graphene structure in terms of engineering applications and found that this structure has stable chemical and thermal properties, ultralight in nature, high surface area, and outstanding mechanical properties.

Bio-inspired structures are intricate and beautiful, but they cannot be made with traditional fabrication techniques. Because 3DP technologies are so adaptable, they can be used to make structures of any shape [30]. Podroužek et al. [31] mentioned that if 3DP is the future of construction then the structural members will not be limited to linear and solid bodies. Moreover, the form of the structure and the inner infill layers can be of complex geometry which will enable multi-scale optimisation of structures.

2.2.6. Design and simulation tools

Ooms et al. [17] used parametric modelling software to handle complex shapes. Rhinoceros is a popular program for this kind of work which allows the creation of the complex model and modification of geometry using a parametric model. Grasshopper is a software plug-in and visual scripting environment for Rhinoceros. Al-Khalidi and Hatuqay [23] used 3DP to examine the energy efficiency of 3DP buildings under various climatic zones. The wall configurations were created using ANSYS software through which they obtained thermal transmittance values. To determine the designed structure's energy demand, the data was entered in Autodesk-Revit 2019 and the energy simulation software Green Building Studio (GBS).

2.3. Findings

This review defines the viability of nature-inspired geometry in the application of 3DPBE that could have better structural and thermal performance. The number of articles containing 3DPBE as the core topic is far lower. The burst in 3DPBE research articles happened in the year 2017, during which the number of publications crossed more than 10. The scientific map on keyword co-occurrence generated through the VOS viewer is shown in Fig. 9, which indicates the keywords co-occurrence trend from 2017. The trend shows keywords such as biomimicry, bio-inspired, and nature-inspired are missing whereas the keywords such as biology, building energy model, etc., are relatively small, compared with the keywords 3D printers, additive manufacturing, construction process, etc.

The findings from the theme analysis suggest that 3DCP requires design innovation and innovative building materials. The design innovation by applying nature inspiration can provide thermal regulation for climate-responsive building envelopes. A multi-scale approach to design optimisation will lead to organic streamlined structures with bio-inspired infill patterns. Even though there are multiple challenges in concrete 3DP, accepting 3DP as the future of building construction, enables multi-scale optimisation of the outer shape of the structure and inner infill configuration. Modern design and modelling software like Rhino3D and Grasshopper are efficient tools in the creation and modification of complex geometry. Moreover, simulation software like Ansys and Ecotect is effective to test the structural, thermal, and energy performance of a building. Most articles acknowledged that 3DP as a future would offer greater efficiency in construction by reducing material wastage, lower cost, and faster construction.

3. Discussion

This section discusses the outcome of the review under two scenarios. The first scenario is trend analysis, and the second scenario is future directions. Trend analysis was framed based on different categorisations made in the earlier sections. Each category critically identifies the rationality behind these trends and sum-up the key aspects of the trend.

3.1. Trend analysis

In this first scenario, the trend analysis is performed through the categorisation of themes made in the earlier sections. The 66 articles screened through the PRISMA process were divided into six categories. These categories were thoughtfully framed by identifying the current research trends in 3DPBE (Table 2).

Table 2. Various research trends of 3DPBEs from the key articles.

Authors	Title	Year	Theme / Trends
Jassmi et al. [21]	Large-scale 3D printing: The way worward	2018	3D printing / 3D concrete printing
Volpe et al. [18]	Building envelope prefabricated with 3DP technology	2021	3D printing / 3D concrete printing
Van Dessel et al. [26]	Bioinspired building envelopes	2020	Biomimicry
Plessis et al. [4]	Biomimicry for 3D concrete printing: A review and perspective	2021	Biomimicry
Ooms et al. [17]	A parametric modelling strategy for the numerical simulation of 3D concrete printing with complex geometries	2021	Design and simulation
He et al. [24]	Energy-saving potential of 3D printed concrete building with integrated living wall	2020	Energy performance
Alkhalidi and Hatuqay [23]	Energy efficient 3D printed buildings: Material and techniques selection worldwide study	2020	Energy performance
Han et al. [28]	A microscopic shell structure with schwarz's D-Surface	2017	Infill pattern
Podrouzek et al. [31]	Bio-inspired 3D infill patterns for additive manufacturing and structural applications	2019	Infill pattern
Speck et al. [22]	Biomimetic bio-inspired biomorph sustainable? An attempt to classify and clarify biology-derived technical developments	2017	Sustainability
Mohammad et al. [15]	3D concrete printing sustainability: A comparative life cycle assessment of four construction method scenarios	2020	Sustainability

The keywords map developed indicating the linkages between the identified trends are established as follows. 3DP and 3DCP keywords of 3DPBE articles represent almost 50% of the complete articles under study. The rationale behind this high percentage is due to the new technology of 3DP which is majorly contrasting from traditional construction. Hence, this field is more attractive for researchers. The trend in 3DPBE design includes the application of the bio-inspired 3D infill. Other identified trends are energy performance, structural strength, applying parametric modelling techniques to bring forward more sustainable 3DPBE design, and devising the buildings much more responsive to the climatic conditions. Most of these trends are engaged in the positive direction of realistic design optimisation for 3DPBEs which is achieved through three important aspects of design structure, architecture, and sustainability.

3.2. Future directions

In the second scenario, the future directions are proposed based on the research gaps identified from the review and analysis of the themes. Looking at the relationship between 3DPBE design and construction processes, bio-inspired geometry infill patterns have been discussed [22, 31], structural and thermal performance enhancement through a design optimisation approach has been presented [23]. Comprehensive research that combines bio-inspired geometry, design optimisation, and new techniques will give an all-inclusive conclusion on the paths to improve 3DPBE design and construction methods. To find a solution that can bring a balance between optimum design, construction, and operation of a 3DP building, in-depth research may be needed. Apart from these future directions, the most important aspects are the formulation of codes and standards for the design of the 3DPBE module are needed.

4. Conclusion

Bio-inspired 3DPBE is still in its infancy, this review has highlighted the potential of research on this topic. The authors have systematically analysed the viability, trends, and features of 3DPBE. The number of previous literature available was too small to build enough conclusions. In today's context, the 3DPBE design and construction is the primary research trend, as the world is ambitious to adopt 3DP in mass housing. Finally, the most crucial aspect of this review is to give future directions in 3DPBEs research which are listed below.

- Testing of the new innovative nature-inspired 3DPBE for its structural and thermal performance to understand the benefit and applicability.
- Various eco-friendly materials need to be tried for their ease of construction and for improving the performance of the 3DPBEs.
- The formation of 3DP building standards and codes are required to foster standardisation in design and construction.
- Life cycle assessments of these modern buildings are required to understand the environmental impact, sustainability, and resilience.

3DP is considered the future of building construction and the modern world is enthusiastic to adopt this new technology. Except for some countries, not much research done on this new technology. Finally, the authors would like to recommend that this review could be build-up further by including more papers searched through other sources.

5. Limitations

For this study, the Scopus database is the only database source used to find papers related to the topic. The reason for selecting Scopus as a database search engine is due to the availability of a relatively broad scope of journals covered in the field of construction and architecture research. This study has included only the articles published in English. The publication year is limited between 2011 to 2021 and the publication type is limited to Articles, conference papers, and review papers.

Abbreviations

3DP	3D Printing
3DCP	3D Concrete Printing
3DPBE	3D Printed Building Envelope
AM	Additive Manufacturing
CAD	Computer Aided Design
LCA	Life Cycle Assessment
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
TPMS	Triply Periodic Minimal Surfaces

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