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COMPUTER AIDED THEMATIC REVIEW AND ANALYSIS OF 3D CONCRETE PRINTED BUILDING |ENVELOPES INSPIRED BY NATURE

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Abstract

3D Concrete Printing (3DCP) is a promising technology gaining rapid development in the recent past. Numerous reviews focused on 3D printing (3DP) in construction but very few reviews on nature-inspired 3DCP. Therefore, a thematic review of current trends in nature-inspired 3DCP is needed. Thematic reviews conducted manually are time-consuming and require repeated and in-depth reading. In recent times, researchers have reasoned using coding for literature studies. Therefore, this study is aimed to synthesise literature for the application of nature-inspired strategies into 3DCP building envelopes using Computer Aided Qualitative Data Analysis Software (CAQDAS). To achieve the goal a CAQDAS tool was implemented for Systematic Literature Review (SLR) and Thematic Content Analysis (TCA) in the five identified thematic areas such as 3D concrete printing, biomimicry, thermal and energy performance, infill patterns, and simulation tools. This study is limited to the last 10 years of literature from the Scopus database. In order to conduct the SLR and TCA, a three-step methodology was adopted. The first step was to plan the review; the second step was to systematically search and screen the relevant literature; and the third step was to synthesis and report the extracted data in the respective thematic categories. The outcome of SLR fetched 36 articles relevant to the topic whereas TCA established a relationship between the various identified themes and synthesised the existing knowledge in the field of 3DCP. The findings from the TCA showcased that the optimisation of the building envelope improved the structural, thermal, and energy performance of the 3DCP buildings and their contribution to the overall sustainability potential. The significance of this analysis describes the current trends in this field and adds beneficial insights into determining the sustainable aspects of 3DCP building envelopes in terms of optimising the structural, thermal, and energy performance. The contribution to this review has shown the benefits of bioinspired design application in the 3DCP and listed the future research areas for the researchers.

Keywords: ATLAS.ti, Biomimicry; Simulation, Sustainability, Systematic review.

1. Introduction

Nature is a great teacher and a guide, inspires humanity to seek and learn the truth in her workings, creations, cycles, and balance. Biomimicry is an innovative process inspired by nature and solving human challenges for sustainability. According to Zari, biomimicry can either be approached problem-based or solution based [1]. Biomimicry is the need of today's world that is threatened by climatic changes and environmental degradation. In the built environment, the application of biomimicry to building envelopes is limited [2].

3D Concrete Printing (3DCP) is an upcoming technology in the field of construction and has attracted significant research in the field of construction owing to its benefits of time, cost, and reduced material wastage [3]. In comparison to traditional construction types, 3DCP has gained considerable benefits in handling complex shapes and designs. When it comes to complex design and automation, 3DCP has an edge over other construction methods and therefore the commercial success lies with the architects and engineers to design robust manufacturing components and processes [4]. The ultimate purpose of a literature study is to identify the relationship between theory, concepts, and practices and thereby appraise the discourse of a subject or problem [5].

Numerous reviews focused on 3DP in construction but very few reviews on nature-inspired 3DCP. A review paper by du Plessis [3] outlined the basic idea of bioinspired 3DCP and mentioned the value of more studies in this direction by future researchers. Therefore, a thematic review of current trends and an in-depth analysis of nature-inspired 3DCP is needed. Thematic reviews conducted manually are time-consuming and require repeated and in-depth reading for processing and evaluating large data [6]. Only recently researchers are using software for literature reviews. The application of CAQDAS in data analysis contributes significantly to establishing a relationship between the researcher and the data [7]. ATLAS.ti, a Computer Assisted Qualitative Data Analysis Software (CAQDAS) offers researchers to speed up the wearisome job and express qualitative information through coding, data query, and network visualisation.

This study is aimed to systematically review and synthesise literature on the application of nature-inspired strategies into 3DCP building envelopes using CAQDAS. The research questions posed are:

1) How does the application of nature-inspired strategies help to optimise the performance of 3DCP buildings?
2) What are the current trends and future directions of bioinspired 3DCP?

The objective of this study is to conduct a Systematic Literature Review (SLR) and Thematic Content Analysis (TCA) using the CAQDAS tool ATLAS.ti in the identified five thematic areas: 3DCP, biomimicry, thermal and energy performance, infill patterns, and simulation tools.

2. Nature Inspired Architecture

The built environment, for a long period of time, has taken inspiration from nature. In the past, numerous studies and scientific research have been conducted on bioinspired strategies in architecture and built environments. Biomimicry in

architecture has seen several applications in building structures, thermal regulation, energy saving, natural lighting, water management, etc. Some of these applications can be seen in the forthcoming paragraphs.

2.1. Bioinspired structures

The structure of living organisms has unique geometries which enable them to adapt and survive any adverse impact posed by the environment [8]. The biomimicry approach is not about aping nature in its physical form but also about mimicking the methods and principles based on the problem and giving intelligent solutions for an efficient structural design [9]. The bioinspiration of the Venus flower basket was mimicked in Gherkin Tower, London (as shown in Fig. 1). The application of a lattice-like exoskeleton structure to the building structure minimises the wind deflection to the ground level [3].

Fig. 1. Gherkin Tower, London (bioinspiration-Venus flower basket sponge) and structural design elements from nature [3].

2.2. Bioinspired thermoregulation

The thermoregulation of the buildings can be efficiently achieved by controlling the heat gain through the building envelopes. The bioinspiration of the termite mound is applied in the Eastgate Centre, Harare, Zimbabwe (as shown in Fig. 2). The termites control the ventilation inside the mound through the stack effect. Similarly, the increase in interior temperature opens the ventilation tubes and cools the building [9].

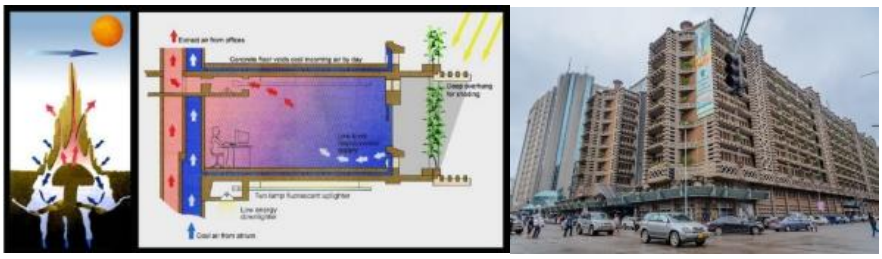

Fig. 2. The Eastgate Centre, Harare (bioinspiration - termite mound) [9].

2.3. Bioinspired natural lighting

The soap film in the bubbles has the ability to reduce the outer surface area and energy. The geometry of soap bubbles appears to be random and organic but it's purely regular and proved to be more efficient to subdivide a space. The National Aquatic Centre, Beijing has taken the bioinspiration from soap bubbles (as shown in Fig. 3). By mimicking the soap bubbles in the building facade, the energy consumption is reduced by 30% and the reduction in artificial lighting by 55% [10].

Fig. 3. National Aquatic Centre, Beijing (bioinspiration-soap bubbles) [10].

2.4. Bioinspired energy saving

The thorn-like structures on the durian fruit are basically for its protection and the same is mimicked in Esplanade Theatre, Singapore in their roofing which acts as a sunshade (as shown in Fig. 4). The dynamic form of the curved roof exhibits a sense of tranquillity and reflects the traditional Asian culture [10].

Fig. 4. Esplanade Theatre, Singapore (bioinspiration-durian fruit) [10].

3. Method

A Systematic Literature Review (SLR) and Thematic Content Analysis (TCA) were conducted to investigate the current trends and identify the future research directions in the 3DCP building envelopes inspired by nature. The SLR and TCA were conducted in three stages: Stage 1 is planning the review by formulating research questions and selecting keywords and databases. Stage 2 is conducting the review by searching the databases through identified keywords and screening the articles. Stage 3 is reporting the screened articles by data coding & analysis done through ATLAS.ti 9 software and reporting the findings.

ATLAS.ti a data analysis software is used in this study to conduct the thematic analysis. Based on the research questions and code-specific sections of research articles, an analysis framework is created using ATLAS.ti [11]. The coding was framed in line with the identified themes mentioned in section 4. The ability of 3DP for advancing nature-inspired research has lately been studied by Arumugam et al. [12] and provides a well-timed review of the application of bioinspired strategies in 3DCP.

3.1. Stage 1-planning the review

In this stage, the research questions for the SLR and the TCA were formulated to achieve a clear and concise answer: 1) How does the application of nature-inspired strategies aid to optimise the performance of 3DCP buildings? 2) What are the current research trends and future directions of bioinspired 3D concrete printing? The keywords related to the topic are identified under three different categories as shown in Table 1. The database used to look for the articles is Scopus and the reason behind choosing Scopus was the availability of a large volume of quality articles on social science and construction compared to other databases like Web of Science, Google Scholar, etc.

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*

3.2. Stage 2-conducting the review

A bibliographic database Scopus, comprising a wide scope of journals related to social science and humanities, was used for searching relevant literature. The key search string, formed by combining the search text from three categories as shown in Tab. 1 is used to search articles in the Scopus database. The search results in producing 203 articles matched at least one term in the article title, abstract, or keywords, are extracted. The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) process is shown in Fig. 5.

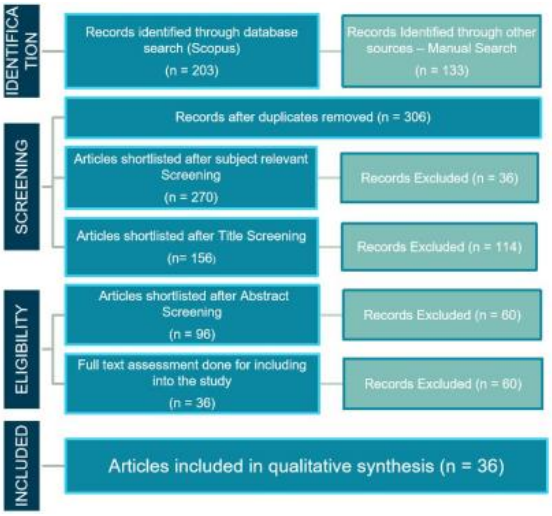

Fig. 5. Systematic review screening process as per PRISMA guidelines.

The articles were searched through other sources and manually fetched about 133 articles. Therefore, a total of 336 articles were taken to Mendeley Desktop to remove

duplicates. Then the number of articles is reduced to 96 after initial screening of the titles and abstracts. An in-depth screening was carried out using Rayyan, a systematic review tool for organising and screening research articles. Finally, after various stages of screening the net number of articles included for the qualitative synthesis is 36.

3.3. Stage 3-reporting

The selected 36 articles were uploaded to ATLAS.ti 9, a thematic analysis software that is most trusted for coding and analysing qualitative data. Out of the 36 articles, only three articles [3, 13, 14] are associated with bioinspired 3D printing. Among these three articles only du Plessis et al. [3] has reviewed biomimetic application in 3D concrete printing as the other two articles discussed biomimetic application in plastic and metal 3D printing.

4. Results and Findings

The initial analysis of 36 systematically reviewed articles gave rise to five themes: 1) Structural optimisation of 3D concrete printing; 2) Bioinspiration / Biomimicry application; 3) Computation / Simulation assessment; 4) Design optimisation of the Infill patterns: 5) Enhanced Thermal / Energy performance. These themes provided the answers to the research questions. The results and findings of the TCA under these five themes are established through ATLAS.ti 9 and presented in this section. The relationship between the themes is shown using the Sankey diagram in Fig. 6.

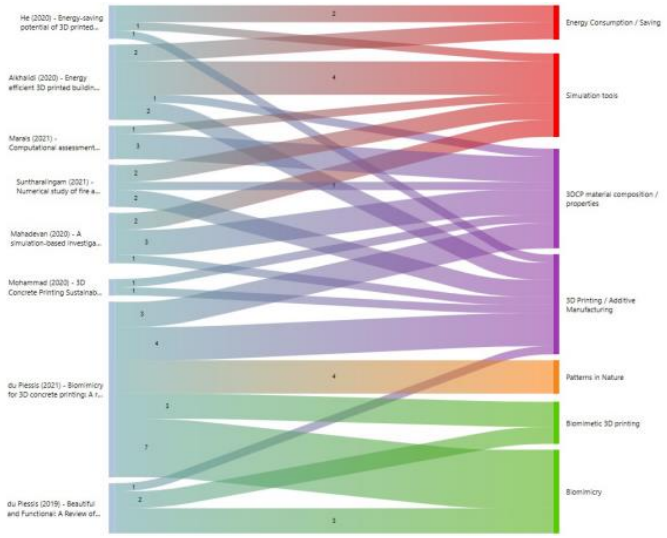

Fig. 6. Sankey diagram-relationship of themes in the literature.

4.1. Structural optimisation of 3DP and 3DCP

The 3DCP material composition and direction of the print layers alters its mechanical properties. The 3DP methods, different materials, and the compositions of materials used in 3DP construction under various studies are shown in Fig. 7.

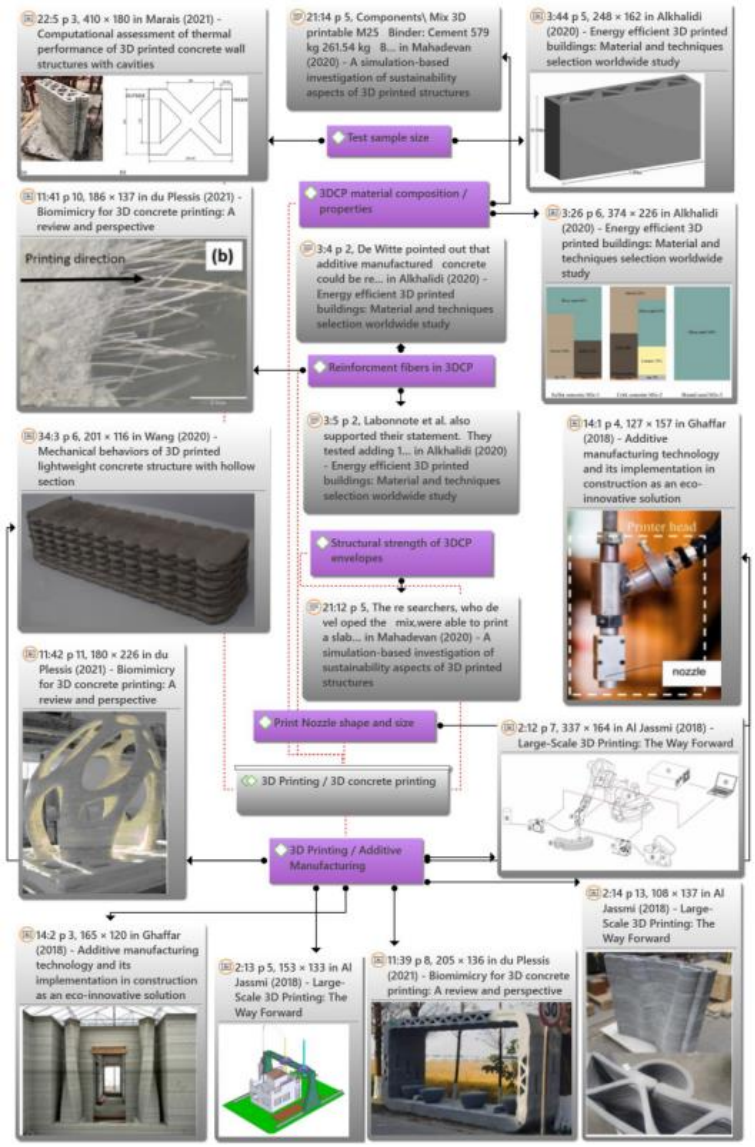

Fig. 7. Structural optimisation of 3DCP-material composition used in various research [3, 15-20].

In the study conducted by Rahul et al. [21], the structural aspects of the 3DCP elements were examined by performing compressive and flexural strength tests in various directions of the load to analyse the printed concrete's anisotropic aspects. The results of the study showed a lower compressive strength of 12 to 22% in printed concrete compared to the solid concrete sample. However, the flexural strength is increased by 13 to 20% providing a maximum bending moment in comparison to the solid concrete sample. A similar study by Joergensen et al. [22], found the compressive strength of 3DP samples to be lower by 12 to 22 MPa in comparison to the solid concrete.

Therefore, the biological inputs in the structural designs and the mimicked natural structures can help to optimise the behaviour of the 3D printed concrete. The experimental investigation carried out by Pham et al. [23], applied Bouligand structures (helicoidal sequences) found in the Lobster shell to print different 3D printed layers as a nature-inspired pattern. They observed an increase of 26.5% in the compressive strength of 3D printed concrete by altering the printing pattern from unidirectional to helicoidal patterns, with the same material mix. Similarly, the flexural strengths of samples with a 10-degree angle helicoidal pattern showed significantly higher performance than the zero-degree or other angles.

4.2. Bioinspiration/biomimicry application

Nature uses optimal materials and works on the concept of "just enough", thereby avoiding material wastage. Figure 8 shows the implementation of bioinspired design in architectural design and product design. The review paper by du Plessis [3], clearly stated that the bioinspired designs have tremendous potential in shaping the future of 3D concrete printing. The study by Wang et al. [24], provide researchers the option of exploring structures inspired by nature with multi-material or composite materials used to make complicated structures using 3DP. Their studies show the effective way of implementation of bioinspired 3DP technique from nano to macro scale.

4.3. Computational/simulation assessment

3DCP is an amateur technology and large-scale printing requires a keen apprehension of the 3DP process. Therefore, a process simulation to verify virtually the possibility of printing is required to avoid numerous expensive physical experiments. The study by Vantyghem et al. [25], shows how the VoxelPrint and CobraPrint a grasshopper plugin can be used to design 3DCP simulation and how these files can be exported to use as an input file for simulation in Abaqus for numerical study. Suntharalingam et al. [26], performed the study on the behaviour of fire and energy on lightweight 3DCP using Alkhalidi and Hatuqay [15] who used Ansys and Green building studio for thermal and energy simulations (as shown in Fig. 9).

4.4. Design optimisation of the Infill patterns

Cellular structures are the most common patterns found in nature. It provides exceptional structural properties when mimicked in 3D printing infill patterns and delivers unique responses. The review papers by du Plessis [3] and Ha and Lu [30] have listed the advantages of bioinspired cellular patterns in 3DP. Figure 10 shows the bioinspired 2D and 3D infill pattern design optimised for 3DP, displayed higher structural strength than grid or sawtooth patterns.

4.5. Enhanced Thermal / Energy performance

The papers of Alkhalidi and Hatuqay [15], Sutharalingam et al. [26], Pessoa et al.[38], and Mahadevan et al. [16] have clearly shown that the thermal performance of 3DCP building envelopes has increased substantially with the combination of insulation in the void spaces. However, the papers of Marais et al. [17], and He et al. [39], have assessed the thermal and energy performance of building envelopes with different cavities and living wall systems (as shown in Fig. 11). The results of these studies indicated excellent energy-saving potential and increased thermal comfort.

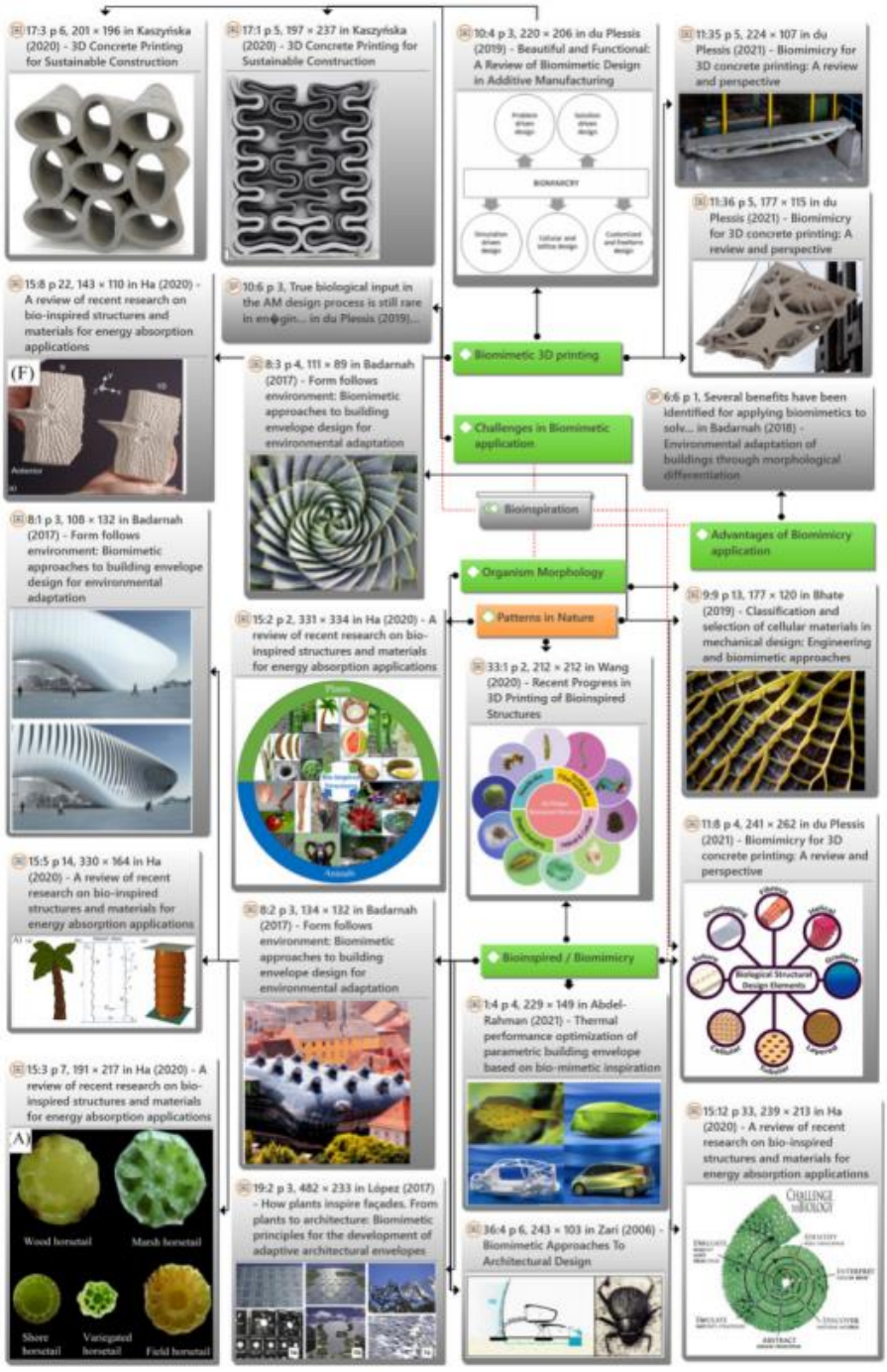

Fig. 8. Bioinspiration/biomimicry applications-Nature's inspirations in architectural design [1, 3, 13, 24, 27-32].

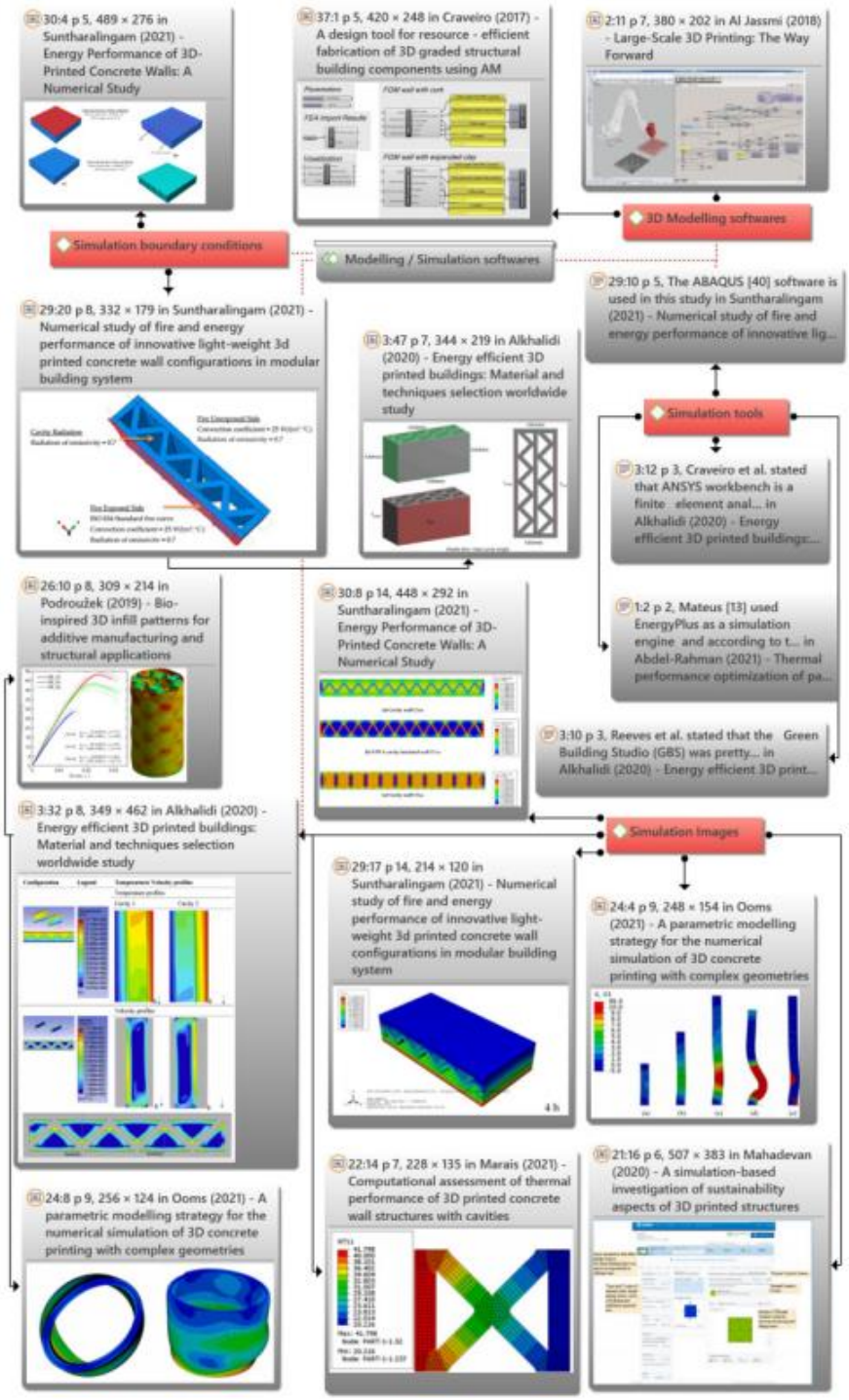

Fig. 9. Computational/simulation assessment used in various 3DP research [14-18, 26, 33-35].

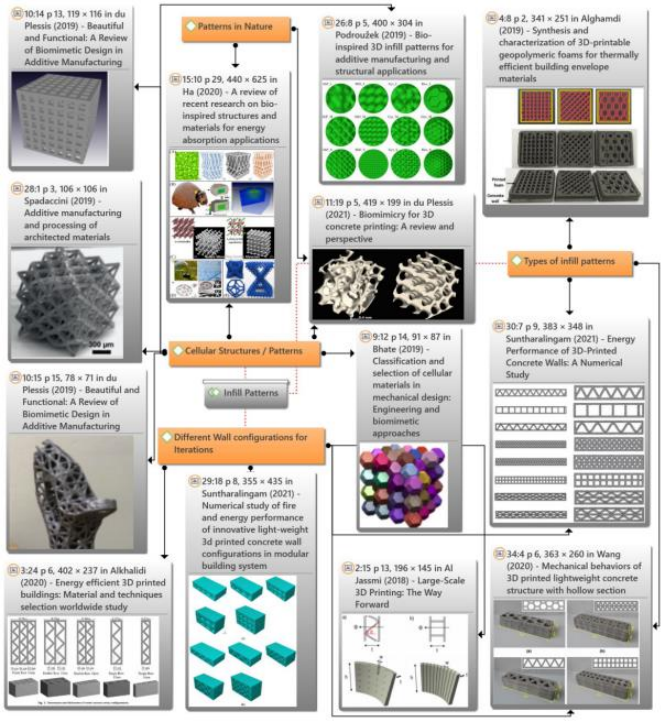

Fig. 10. Infill patterns-Different 2D cellular patterns to 3D gyroid patterns discussed in various [3, 13-15, 18, 20, 26, 29, 35-37].

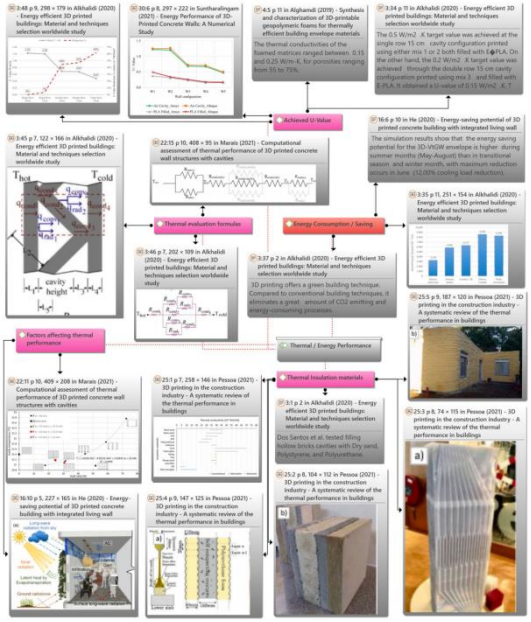

Fig. 11. Thermal and energy performance of 3DP envelopes - Results and computations from various studies [3, 15, 17, 35, 36, 38-40].

5. Discussion

Bioinspired and sustainable development follow biomimetic strategies, and hence they are discussed in this section to provide a clear-cut understanding in the context of optimising the structural, thermal, and energy performance of 3DCP building envelopes. The findings from the 36 literature studies show the current trends in 3DCP which mainly focuses on the materials and the mix proportions of the materials to achieve better strength and buildability of the 3DCP walls. However, some studies highlighted the capacity of 3DCP envelopes' thermal and energy performance to be more efficient than conventional walls when insulation material is added to their cavities. Furthermore, the identified five themes highlighted the potential of bioinspired strategies when applied to 3DCP technology to increase structural performance and reduced material usage.

This review used relevant literature and categorized the themes based on the viability criteria of the application of bioinspired strategies into 3DCP. This section is intended to act as a guide for future researchers to further poise the scale between biomimicry and 3DCP. The ideas for future research were identified from the TCA based on the gaps found in the literature. Biomimicry has a great potential for future research in 3DCP and an effective application of bioinspired complex forms will enhance the structural, thermal, and energy performance of 3DCP building envelopes. Future research needs to tap the unique potential and capabilities of 3DCP technology to produce complex designs seen in nature.

The authors have analysed and outlined the basic idea of bioinspired 3DCP and its up to future researchers to establish and create new construction ideas. A comprehensive study and in-depth research combining bioinspired concepts, 3DCP technology, and advanced simulation methods are recommended. The outcome of the current study and the future directions are listed below.

- Cost and time factor comparison between conventional construction, 3DCP construction, and bioinspired design implemented with 3DCP construction.
- Evaluating innovative bioinspired design ideas in large-scale 3DCP applications.
- Fire and acoustic performance evaluation of bioinspired 3DCP construction.
- Framing of standards and codes for material and construction standardisation.
- Quantifying the benefits of bioinspired design and testing the sustainability aspects.

6. Conclusion

The inspiration for conducting a thematic review using ATLAS.ti 9 software was drawn to showcase 3DCP technology as the future of the construction industry and the world is interested in this modern construction technology. Countries like China, UAE, USA, etc. are pushing for this technology due to its benefits of cost and time. This study aimed to review the literature on 3DCP technology and bioinspired design and guides the researchers to imagine the future fusion between biomimicry and 3DCP. The application of bioinspired/biomimetic design in 3DCP is hardly seen in any of the reviewed articles. However, some applications are seen in the plastic and metal 3D printing which showcased significant improvement in the structural and thermal performance of those 3D printed models.

This study is most likely the first TCA that aims at 3DCP and the potential application of biomimicry in 3DCP. The key success of the implementation of bioinspired patterns in 3DCP lies in the understanding of the basics of bioinspired design and the limitations of 3DCP technology. 3DCP technology is the future of sustainable construction due to its increased building efficiency, reduction of construction waste, and reduced carbon footprint. From this review, it is evident that even though many buildings have been printed and put into use, a lot of effort is needed to understand their full potential. Moreover, this study can be further enhanced by including more literature from other sources and other languages apart from English.

7. Limitations

The database search for extracting the literature related to the research questions is limited to Scopus. The source type is limited to journals and the year of publication between 2011 to 2021. The language selection of the literature is limited to English.

Abbreviations

3DP	3D Printing
3DCP	3D Concrete Printing
CAQDAS	Computer Assisted Qualitative Data Analysis Software
SLR	Systematic Literature Review
TCA	Thematic Content Analysis

References

1. Zari, M.P. (2007). Biomimetic approaches to architectural design. *Proceedings of the Sustainable Building Conference* (*SB07*), Aukland, New Zealand, 33, 1-11.
2. Webb, M. (2021). Biomimetic building facades demonstrate potential to reduce energy consumption for different building typologies in different climate zones. *Clean Technologies and Environmental Policy*, 24(2), 493-518.
3. Du Plessis, A.; Babafemi, A.J.; Paul, S.C.; Panda, B.; Tran, J.P.; and Broeckhoven, C. (2021). Biomimicry for 3D concrete printing: A review and perspective. *Additive Manufacturing*, 38, 101823.
4. Buswell, R.A.; Leal de Silva, W.R.; Jones, S.Z.; and Dirrenberger, J. (2018). 3D printing using concrete extrusion: A roadmap for research. *Cement and Concrete Research*, 112, 37-49.
5. Onwuegbuzie, A.J.; and Weinbaum, R. (2017). A framework for using qualitative comparative analysis for the review of the literature. *The Qualitative Report*, 22(2), 359-372.
6. Scales, B.J. (2013). Qualitative analysis of student assignments: A practical look at ATLAS.ti. *Reference Services Review*, 41(1), 134-147.
7. Goble, E.; Austin, W.; Larsen, D.; Kreitzer, L.; and Brintnell, S. (2012). Habits of mind and the split-mind effect: When computer-assisted qualitative data analysis software is used in phenomenological research. *Forum Qualitative Social Research* (*Soczialforschung*), 13(2), 1-22.

8. Arumugam, G.; Abidin, S.N.Z.; Kusumo, C.M.L.; and Jain, A. (2023). Teaching nature and architecture: student-led account of biomimicry innovations in the tropics. *Biomimetics*, 8(1), 13.
9. Jamei, E.; and Vrcelj, Z. (2021). Biomimicry and the built environment, learning from nature's solutions. *Applied Sciences (Switzerland)*, 11(16), 7514.
10. Radwan, G.A.N.; and Osama, N. (2016). Biomimicry, an approach, for energy efficient building skin design. *Procedia Environmental Sciences*, 34, 178-189.
11. Smit, B.; and Scherman, V. (2021). Computer-assisted qualitative data analysis software for scoping reviews: A Case of ATLAS.ti. *International Journal of Qualitative Methods*, 20, 1-3.
12. Arumugam, G.; Lavanyapriya, K.P.; Kusumo, C.M.L.; and Mari, T. (2022). A systematic review and analysis of 3d printed building envelopes inspired by nature. *Journal of Engineering Science and Technology* (*JESTEC*), Special Issue on STAAUH, 58-73.
13. Du Plessis, A.; Broeckhoven, C.; Yadroitsava, I.; Yadroitsev, I.; Hands, C.H.; Kunju, R.; and Bhate, D. (2019). Beautiful and functional: A review of biomimetic design in additive manufacturing. *Additive Manufacturing*, 27, 408-427.
14. Podroužek, J.; Marcon, M.; Ninčević, K.; and Wan-Wendner, R. (2019). Bio-inspired 3D infill patterns for additive manufacturing and structural applications. *Materials*, 12(3), 499.
15. Alkhalidi, A.; and Hatuqay, D. (2020). Energy efficient 3D printed buildings: Material and techniques selection worldwide study. *Journal of Building Engineering*, 30, 101286.
16. Mahadevan, M.; Francis, A.; and Thomas, A. (2020). A simulation-based investigation of sustainability aspects of 3D printed structures. *Journal of Building Engineering*, 32, 101735.
17. Marais, H.; Christen, H.; Cho, S.; de Villiers, W.; and van Zijl, G. (2021). Computational assessment of thermal performance of 3D printed concrete wall structures with cavities. *Journal of Building Engineering*, 41, 102431.
18. Al Jassmi, H.; Al Najjar, F.; and Mourad, A.H.I. (2018). Large-scale 3D printing: The way forward. *IOP Conference Series: Materials Science and Engineering*, 324, 012088.
19. Ghaffar, S.H.; Corker, J.; and Fan, M. (2018). Additive manufacturing technology and its implementation in construction as an eco-innovative solution. *Automation in Construction*, 93, 1-11.
20. Wang, L.; Jiang, H.; Li, Z.; and Ma, G. (2020). Mechanical behaviours of 3D printed lightweight concrete structure with hollow section. *Archives of Civil and Mechanical Engineering*, 20(1), 1-17.
21. Rahul, A.V.; Santhanam, M.; Meena, H.; and Ghani, Z. (2019). Mechanical characterisation of 3D printable concrete. *Construction and Building Materials*, 227, 116710.
22. Joergensen, H.B.; Douglas, P.J.; and Naboni, R. (2021). Experimental study on the Anisotropic behaviour and strength of 3D printed concrete. *Proceedings of the Fib Symposium 2021 Held Online from Lisbon, Portugal*,739-748.

23. Pham, L.; Lu, G.; and Tran, P. (2020). Influences of printing pattern on mechanical performance of three-dimensional-printed fiber-reinforced concrete. *3D Printing and Additive Manufacturing*, 9(1), 1-19.
24. Wang, D.; Chen, D.; and Chen, Z. (2020). Recent progress in 3D printing of bioinspired structures. *Frontiers in Materials*, 7, 1-10.
25. Vantyghem, G.; Ooms, T.; and De Corte, W. (2021). VoxelPrint: A Grasshopper plug-in for voxel-based numerical simulation of concrete printing. *Automation in Construction*, 122, 103469.
26. Suntharalingam, T.; Gatheeshgar, P.; Upasiri, I.; Poologanathan, K.; Nagaratnam, B.; Rajanayagam, H.; and Navaratnam, S. (2021). Numerical study of fire and energy performance of innovative light-weight 3D printed concrete wall configurations in modular building system. *Sustainability (Switzerland)*, 13(4), 2314.
27. Abdel-Rahman, W.S.M. (2021). Thermal performance optimization of parametric building envelope based on bio-mimetic inspiration. *Ain Shams Engineering Journal*, 12(1), 1133-1142.
28. Badarnah, L. (2017). Form follows environment: Biomimetic approaches to building envelope design for environmental adaptation. *Buildings*, *7*(2), 40.
29. Bhate, D.; Penick, C.A.; Ferry, L.A.; and Lee, C. (2019). Classification and selection of cellular materials in mechanical design: Engineering and biomimetic approaches. *Designs*, 3(1), 19.
30. Ha, N.S.; and Lu, G. (2020). A review of recent research on bio-inspired structures and materials for energy absorption applications. *Composites Part B: Engineering*, 181, 107496.
31. Kaszyńska, M.; Skibicki, S.; and Hoffmann, M. (2020). 3D concrete printing for sustainable construction. *Energies*, 13(23), 6351.
32. López, M.; Rubio, R.; Martín, S.; and Croxford, B. (2017). How plants inspire façades. From plants to architecture: Biomimetic principles for the development of adaptive architectural envelopes. *Renewable and Sustainable Energy Reviews*, 67, 692-703.
33. Craveiro, F.; Bartolo, H.M.; Gale, A.; Duarte, J.P.; and Bartolo, P.J. (2017). A design tool for resource-efficient fabrication of 3d-graded structural building components using additive manufacturing. *Automation in Construction*, 82, 75-83.
34. Ooms, T.; Vantyghem, G.; Van Coile, R.; and De Corte, W. (2021). A parametric modelling strategy for the numerical simulation of 3D concrete printing with complex geometries. *Additive Manufacturing*, 38, 101743.
35. Suntharalingam, T.; Upasiri, I.; Gatheeshgar, P.; Poologanathan, K.; Nagaratnam, B.; Santos, P.; and Rajanayagam, H. (2021). Energy performance of 3D-printed concrete walls: A numerical study. *Buildings*, 11(10), 432.
36. Alghamdi, H.; and Neithalath, N. (2019). Synthesis and characterization of 3D-printable geopolymeric foams for thermally efficient building envelope materials. *Cement and Concrete Composites*, 104, 103377.
37. Spadaccini, C.M. (2019). Additive manufacturing and processing of architected materials. *MRS Bulletin*, 44(10), 782-788.

38. Pessoa, S.; Guimarães, A.S.; Lucas, S.S.; and Simões, N. (2021). 3D printing in the construction industry - A systematic review of the thermal performance in buildings. *Renewable and Sustainable Energy Reviews*, 141, 110794.
39. He, Y.; Zhang, Y.; Zhang, C.; and Zhou, H. (2020). Energy-saving potential of 3D printed concrete building with integrated living wall. *Energy and Buildings*, 222, 1-13.
40. Mohammad, M.; Masad, E.; and Al-Ghamdi, S.G. (2020). 3D concrete printing sustainability: A comparative life cycle assessment of four construction method scenarios. *Buildings*, 10(12), 245.