Journal of Building Engineering 127 (2026) 116323

Contents lists available at ScienceDirect

Journal of Building Engineering

journal homepage: www.elsevier.com/locate/jobe

Advancements in 3D soil printing for construction: Material development and technological challenges

Fathima Nifla [a], Pathmanathan Rajeev [a,*], Satheeskumar Navaratnam [b], Alessio Ferrari [c], Marco Rosone [d], Marco Starvaggi [d], Jay Sanjayan [a], Emad Gad [a]

[a] *Department of Civil and Construction Engineering, Swinburne University of Technology, Australia*
[b] *Institute of Innovation, Science and Sustainability (IISS) Federation University, Ballarat, Australia*
[c] *Swiss Federal Institute of Technology in Lausanne (EPFL), Switzerland*
[d] *University of Palermo, Department of Engineering Palermo, Italy*

ARTICLE INFO

Keywords:
Rheology
Earth-based printing
Extrusion-based printing
Sustainable construction

ABSTRACT

Soil-based 3D printing has emerged as a potential solution for sustainable construction, due to growing concerns over the environmental impact of cement-based materials. However, the limited understanding of soil printability, material behaviour, and performance under real-world conditions remains a significant barrier to its application. This review provides an in-depth evaluation of material performance and technological challenges of soil 3D printing with a special focus on the extrusion-based printing method. Furthermore, this study explores the fresh and hardened state properties of soil-based mixtures, highlighting the importance of rheology in achieving extrudability and buildability during the printing process. Notably, the incorporation of certain additives has been shown to reduce shrinkage by up to 50% and increase compressive strength by 10–30%, although results remain highly dependent on soil type. The environmental assessments indicate that soil 3D printing can reduce the carbon footprint by up to 20% compared to traditional construction methods, especially when local or excavated soils are used. Despite these advancements, challenges persist in standardising mix designs, managing variability in soil composition, and ensuring long-term durability under environmental exposure. To advance soil-based 3D printing in sustainable construction, it is important to integrate soil mechanics principles, standardise testing protocols, and validate results at the field scale.

1. Introduction

Soil has played a pioneering role in construction for centuries, preceding contemporary building materials for thousands of years. Earthen construction has proven to be durable, cost effective and sustainable, from early settlements in Mesopotamia [1] and the Great Wall of China [2] to traditional adobe structures in Africa and Latin America [3]. Even today, approximately 30% of the world's population lives in structures built using some form of soil, making it one of the most universally used construction materials worldwide [4]. The material's abundance, recyclability, and inherent thermal and acoustic properties have long made it suitable for

---

* Corresponding author.
E-mail addresses: niflanausan@swin.edu.au (F. Nifla), prajeev@swin.edu.au (P. Rajeev), s.nava@federation.edu.au (S. Navaratnam), alessio.ferrari@epfl.ch (A. Ferrari), marco.rosone@unipa.it (M. Rosone), marco.starvaggi@unipa.it (M. Starvaggi), jsanjayan@swin.edu.au (J. Sanjayan), egad@swin.edu.au (E. Gad).

https://doi.org/10.1016/j.jobe.2026.116323
Received 26 October 2025; Received in revised form 21 April 2026; Accepted 11 May 2026

diverse architectural needs, from housing to retaining structures. Historically perceived as a low-tech building solution, soil has more recently emerged as a medium of interest in the context of sustainable development and low-carbon construction practices [5].

Currently, soil continues to be utilised in various forms across modern construction applications, including adobe bricks, rammed earth, compressed earth blocks, cob, and hybrid earth-cement materials [6,7]. These methods have gained interest not only in rural and resource-constrained areas but also in innovative architectural projects that prioritise sustainability and energy efficiency. However, soil-based materials are susceptible to moisture variations, which may cause softening and structural deterioration, limiting their applicability in humid or high-rainfall climates without adequate stabilisation [8]. Moreover, compared with modern construction materials such as cement, unfired earth exhibits lower compressive strength, reduced durability under freeze-thaw cycles and greater variability in mechanical performance due to the heterogeneity of naturally occurring soils [8,9]. Therefore, the construction industry worldwide is dominated by the extensive use of Portland cement-based concrete. Globally, cement production is responsible for 5 to 7% of total CO_2 emissions [10], representing a critical challenge to the industry's environmental performance. Considering this, researchers and policymakers are increasingly seeking alternatives that reduce carbon footprint without compromising structural integrity. Soil, when locally sourced and appropriately stabilised, offers a renewable and low-embodied energy alternative, with the potential to complement or replace conventional concrete-based methods in certain applications [5].

In the past two decades, the introduction of digital technologies into construction practices has caused a paradigm shift. Among these, 3D printing and additive manufacturing have gained attention for their ability to revolutionise how buildings are designed and constructed [11]. 3D printing enables automated, layer-by-layer construction of structures directly from digital models, in contrast to traditional construction, which depends on formwork, scaffolding, and manual labour [12]. This approach minimises material waste, reduces labour requirements, and facilitates complex geometries that are difficult to achieve through conventional methods [12]. While most major advancements have already been achieved in the field of 3D concrete printing, the broader general application of 3D printing technology has impacted the development and testing of alternative construction materials, including soil and other earth composites [13–17]. These innovations seek to bridge the gap between automation and sustainability, particularly in the context of eco-conscious construction.

In recent years, the fusion of additive manufacturing with soil as a material has begun to gain scientific and practical attention [13,16,18]. Several 3D-printed earth buildings have been completed in Italy, Spain and the United States, utilising a range of soil-based materials, including locally sourced clay rich soil, raw or minimally processed soil and soil mixes partially stabilised with natural fibres to ensure printability and structural integrity, as depicted in Fig. 1 [19]. This soil-based 3D printing approach brings together the environmental benefits of earthen construction and the precision of digital fabrication. Several experimental studies and prototypes have explored the feasibility of using untreated [17,20,21] and treated soils, including those with natural or industrial additives [22,23], fibres [24–26], and lime [25] for printing load-bearing and non-load-bearing elements. For instance, Gomaa et al. [24], Alqenaee and Memari [25] demonstrated the fabrication and compression testing of 3D printed cob wall and cylindrical elements, showing that 3D printable soil mixes can achieve compressive strengths comparable to conventional earthen masonry. Moreover, Curth et al. [27] study has proved that post-tensionable earthen wall modules can be mass manufactured using digital fabrication. Additionally, research has shown that high fine-grained soils with high clay content can provide favourable rheological characteristics for extrusion, enhancing pumpability and printability [23,28]. Innovative projects have also examined the inclusion of natural fibres, biopolymers like sodium alginate, and recycled aggregates to enhance structural integrity and reduce shrinkage and cracking [15,28]. Furthermore, 3D-printed soil has been used not only in structural components but also in applications such as moisture-regulating interior partitions [29], biologically active prototypes capable of supporting plant growth [30]. These emerging studies highlight the diverse and promising potential of soil-based additive manufacturing for sustainable construction.

Despite growing interest, current research on the 3D printing of soil-based materials is scattered, and the challenges include potential shrinkage and cracking upon drying, as well as the loss of rigidity and strength upon wetting. Furthermore, the issues, including flowability during printing and stability post-deposition, are not well understood. Only a few studies have addressed additive manufacturing with soil [33–37], and each has been limited in scope. For instance, Abdallah et al. [33] explored the architectural design of bio-inspired 3D-printed clay bricks for improved material efficiency by optimising the print path and geometry. The study highlighted geometry as a design strategy for reducing raw material consumption; hence, it remained focused on an architectural


(a) (b)

Fig. 1. 3D printed soil structures (a) TECLA (Italy) [31] (b) Earth Forest campus (Spain) [32].

perspective rather than structural optimisation. Wolf et al. [34] conducted a review of additive manufacturing in clay and ceramic materials, detailing advances up to 2021. Nevertheless, their review primarily focused on ceramic printing in laboratory settings and does not discuss the fresh-state properties and structural performance of large-scale printed soil in construction. Aghaee et al. [35] discussed the evolution of construction 3D printing towards novel approaches (including aerial robotics and extraterrestrial applications), offering a broader perspective but without an emphasis on the material science of printable soil. More recently, Abedi et al. [36] provided a critical review of clay-based composites for 3D-printed cementitious systems. Their work examines how incorporating calcined clays or other local minerals can partially replace cement and improve the sustainability of 3D-printed concrete, including analysis of rheology and mechanical performance in clay-cement mixes. Abedi et al. [36] focused on clay as an additive to cement-based construction, whereas a dedicated analysis on the insights specific to printing with raw or minimally stabilised soil (as the primary material) is still lacking in the literature. On the other hand, Gomaa et al. [37] synthesised research trends in digital earth construction and emphasised the growing application of soil-based 3D printing. While the review discusses the emerging interest in digitally fabricated soil structures, it provides limited discussion on printability limits, testing methods, and mix design strategies across different types of soil. Although these studies emphasise the novelty of 3D printed soil, they reveal an absence of systematic analysis that critically examines the influence of printing technology, soil composition, and additive strategies on printability and performance prediction.

Therefore, this paper aims to address this knowledge gap by systematically evaluating the existing research on soil-based 3D printing within the construction context. The following aspects are considered in this study: (1) the state-of-the-art technologies available for 3D printing of soil, their performance during the printing process; (2) rheological and fresh printed properties of soils and the strength evolution for printed soil; and (3) limitations and challenges associated with 3D printing of soil for construction and potential solutions.

2. Methodology

A systematic approach was developed to identify and evaluate the research literature on soil-based 3D printing, to create new perspectives while ensuring that the findings reflect the current state of the field. The data collection was carried out through the SCOPUS database, which is a high-quality international database for peer-reviewed literature [38]. The preferred reporting items for systematic review and meta-analysis (PRISMA) approach was used for the final selection of the studies that evaluated the fresh and hardened state properties of 3D printed clay and soil (Fig. 2). PRISMA is an established method for guiding the systematic review of scholarly literature and is based on four key steps: (1) identification, (2) screening, (3) eligibility, and (4) inclusion. The process of PRISMA is further elaborated in Appendix A.

The advancement of 3D printing of soil and clay-based material can be analysed in two stages: (1) bibliometric analysis, which provides a quantitative understanding of the research trend and knowledge development within the field, highlighting influential authors, institutions and publication patterns; and (2) content analysis, which offers an in-depth examination of the evolution,

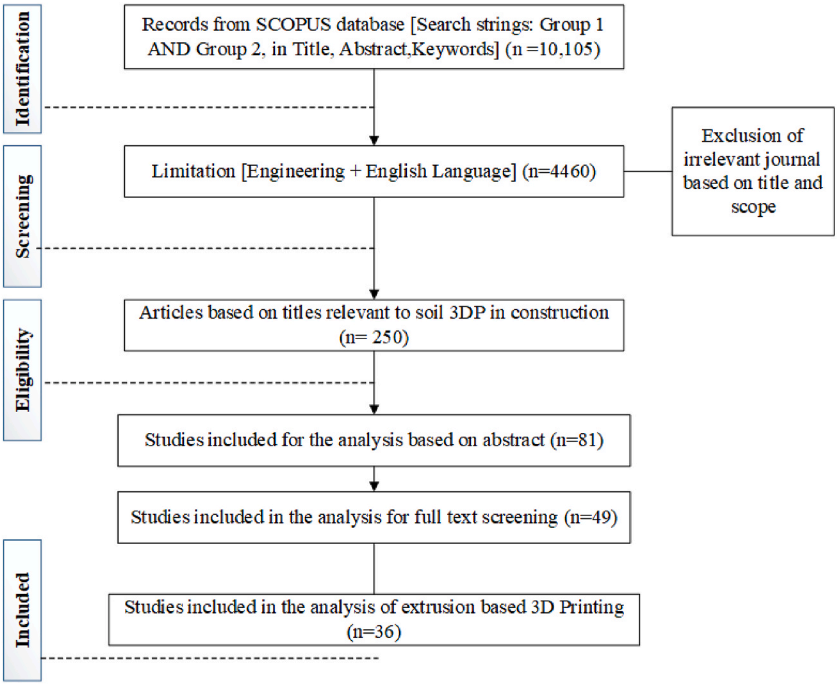


Fig. 2. PRISMA flowchart to identify and select studies relevant to soil 3D printing (3DP).

conceptual frameworks and limitations in literature.

To gain a comprehensive perspective on the advancement of soil-based 3D printing, bibliometric analysis was conducted on 49 journal articles identified through full-text screening. An initial content analysis of these studies was performed, with Table A2 in Appendix A outlining the scope and focus of each study to provide an overview relevant to the main research questions (Symbols used in the table are defined as follows: ✓ indicates investigated in the referenced study; × indicates not investigated in the referenced study). Subsequently, a more detailed content analysis was carried out on the 36 selected studies from Table A2, focusing on extrusion-based 3D printing, due to its potential for large-scale construction applications.

3. Bibliometric analysis

3.1. Article published trend

The number of papers published in the field often reflects its development and the expansion of knowledge within that domain. Fig. 3 illustrates the trend of the annual number of articles on soil-based 3D printing in the engineering domain published over the years. Notably, no specific time period was initially set for the paper selection and screening, nevertheless, the first documented publication in the analysis of 49 journal articles was from 2018. This suggests that the earliest notable studies on 3D printing with soil-based material in the construction industry were not published until 2018 in the engineering domain. This starting point reflects the emerging nature of the field, where the practical application of even 3DP concrete was just beginning to gain popularity in the academic sector.

As per Fig. 3, in the early years, research output in the field was minimal, with only two publications in 2018 and one publication in 2019. This gradual start suggests that during this period, 3D printing technologies, particularly in relation to soil-based materials in construction, were still in the early stages of development. Starting from 2020, a noticeable increase in the number of publications can be observed, with 2023 marking the peak in research contributions with 11 publications. Out of the selected articles, 38 (77.6%) were published in the last four years.

3.2. Journal sources

These shortlisted articles, based on full-text screening, originate from a diverse range of 21 journals. Table 1 provides the list of journals, with the top three journals representing 40% of the total publications. The journal Construction and Building Materials leads the list with a substantial 14 published articles out of a total of 49. Following this, the Buildings and Additive Manufacturing ranks second with 3 peer-reviewed articles each. These findings underscore the prominent role of these journals in disseminating research related to soil and clay-based 3D printing in the construction sector.

In the domain of citation records, as summarised in Table 1 the Construction and Building Materials journal has obtained over 500 citations. The articles from this journal are widely cited and serve as foundational references for subsequent research. Table 2 gives details about the individual article citations and affiliation based on the first author. Leading the citation ranking is the paper titled "3D printing of earth-based materials: Processing aspects" [39] published in 2018, the first documented publication in the analysis, having obtained an impressive 317 citations. These citation metrics underscore the influential contributions of these specific articles to the research in soil and clay-based 3D printing.

To further understand the countries actively involved in research on soil and clay-based 3D printing, a heat map was generated based on the countries affiliated with the first author of each reviewed study, as shown in Fig. 4. It can be noted that the United States of

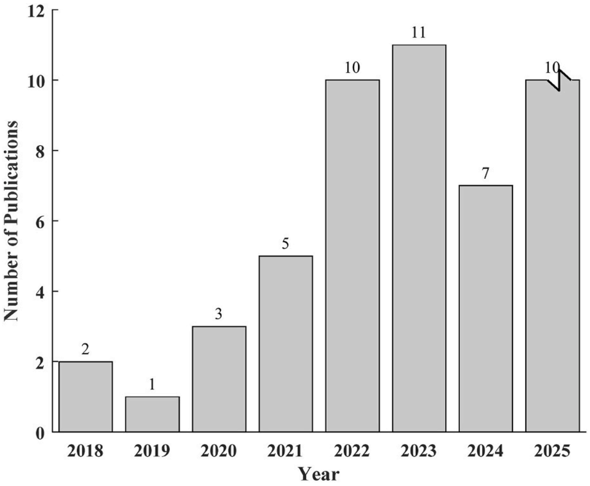


Fig. 3. Publication trend of screened articles based on the abstract from 2018 to the present.

Table 1
List of journals screened based on the abstract.

Source title	Documents	Total citations	Average citations
Construction and Building Materials	14 (28.6%)	659	47
Additive Manufacturing	3 (6.1%)	158	52
Buildings	3 (6.1%)	17	5
Automation in Construction	2 (4.1%)	244	122
Cement and Concrete Composites	2 (4.1%)	158	79
Architectural Science Review	3 (6.1%)	74	24
Engineering Structures	2 (4.1%)	19	9
Rapid Prototyping Journal	2 (4.1%)	8	4
Materials & Design	1 (2%)	35	35
Materials	1 (2%)	32	32
Soil and Rocks	1 (2%)	2	2
Progress in Additive Manufacturing	3 (6.1%)	26	8
Sustainability	1 (2%)	9	9
Soil Dynamics and Earthquake Engineering	1 (2%)	6	6
Journal of Materials in Civil Engineering	1 (2%)	3	3
Tunnelling and Underground Space Technology	1 (2%)	2	2
Journal of Building Engineering	3 (6.1%)	1	0.3
Journal of Engineering Research	1 (2%)	12	12
Structures	1 (2%)	-	-
Architectural Engineering and Design Management	1 (2%)	1	1
Case studies in Construction Materials	1 (2%)	-	-

Table 2
The top 6 articles with the highest number of citations.

Title (Year)	Journal	Affiliation	Citation	Ref
3D printing of earth-based materials: Processing aspects (2018)	Construction and Building Materials	University of Western Brittany (UBO)	317	[39]
3D printing of clay for decorative architectural applications: Effect of solids volume fraction on rheology and printability (2020)	Additive Manufacturing	University of Melbourne	139	[21]
3D printing system for earth-based construction: Case study of cob (2021)	Automation in Construction	University of Adelaide	126	[40]
Robotic 3D clay printing of prefabricated non-conventional wall components based on a parametric-integrated design (2020)	Automation in Construction	University of Cyprus	118	[41]
Rheological properties and compressive strength of construction and demolition waste-based geopolymer mortars for 3D-Printing (2022)	Construction and Building Materials	Hacettepe University	112	[42]
Construction and demolition waste-based geopolymers suited for use in 3-dimensional additive manufacturing (2021)	Cement and Concrete Composites	Hacettepe University	101	[43]

America has generated the highest number of first-author publications (8), while China (6) and Italy (5) have made significant contributions.

4. Content analysis

The printability refers to the properties of a soil mix, encompassing its pumpability, extrudability, and buildability in its fresh or 'green' state. In its hardened state, printability is characterised by compressive, flexural, and tensile strength, along with strong layer-to-layer interaction. These factors are also influenced by the mechanics, dimensions, and configuration of the 3D printing system.

In order to understand the applicability of 3D printing of any material in the construction industry it is necessary to have a comprehensive understanding on the three main domains controlling additive manufacturing, namely the fresh properties (rheological properties crucial for understanding the flow behaviour of 3D printing material prior to printing, extrudability and buildability), hardened properties such as mechanical and thermal behaviour as well as the material properties such as shrinkage and drying behaviour. The analysis of the mechanical properties of the material is of utmost importance for the assessment of its potential application in various construction environments, particularly in the advent of innovative technologies such as 3D printing. Among these properties, compressive strength is of particular significance. The in-depth literature review revealed poor studies on 3D printing of soil components, analysing all three aspects, although some small-scale experiments have been conducted in the construction industry, which is summarised in Table A2. Only 5 studies (10.2%) out of the 49 selected studies have analysed all three aspects [22,28,44–46]. Nevertheless, the thermal behaviour of these materials in the 3D printed state is not yet well established in the 3D printing literature. Only 5 studies (10.2%) have analysed the thermal behaviour of 3D printed soil specimens. Provided that a considerable proportion of the research in 3D printed soil originates from disciplines distant from geomechanics and civil engineering, there is greater interest in the architectural and design aspect of 3D printing technology rather than providing a comprehensive description using physical quantities familiar to soil mechanics such as water content, suction values and porosity index. Moreover, 3D-printed

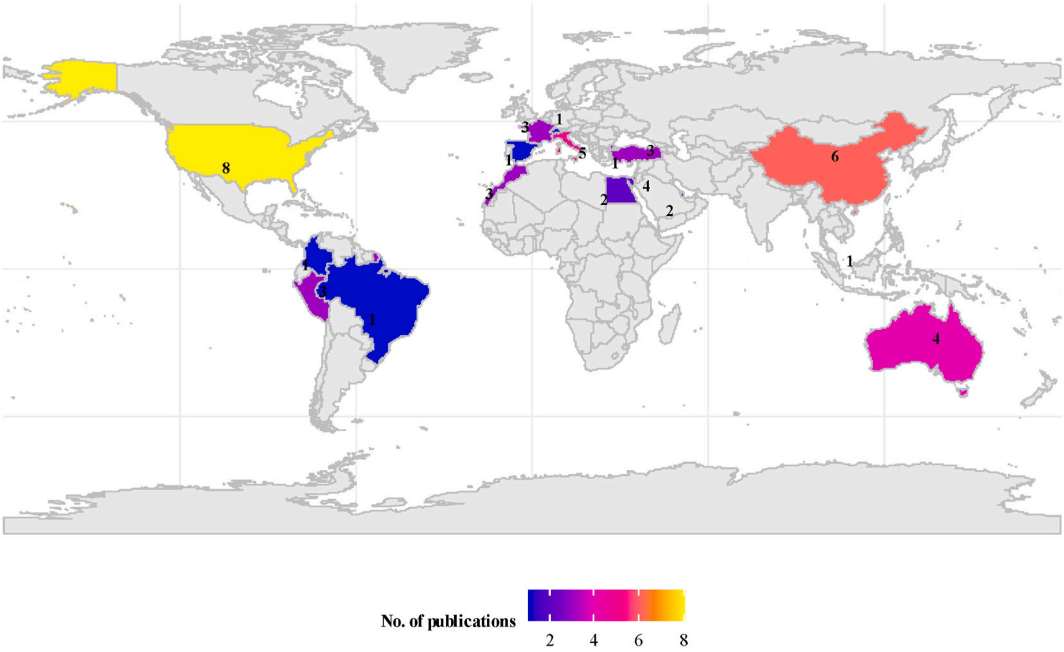


Fig. 4. Global concentration of studies by country of first author affiliation.

soils can exhibit a peculiar double-structured fabric that influences their hydromechanical behaviour [47,48]. In these cases, a distinction between micro- and macro-scale properties needs to be made when the soil is 3D printed.

The following sub-sections synthesise findings from content analysis to depict the current state of soil-based printing in the construction realm. It addresses critical aspects considered in the pre- and post-printing stages of soil printing. This analysis facilitates the identification of common challenges that hinder the application of soil printing in the construction industry. Additionally, it establishes a foundation for proposing potential avenues for future research.

4.1. State-of-the-art technologies for 3D printing with soil

The advancement of 3D printing used for construction applications can be categorised into four main techniques in the literature [12].

(1) Material extrusion: one of the most widely used 3D printing technologies in construction [49]. In this process, material is forced through a nozzle (or extruder) and deposited layer by layer to create a three-dimensional object [50]. This printing process

Table 3
State of art soil 3D printing technologies.

3D printing technology	Description	Advantage	Limitations	Reference
Material extrusion	Continuous deposition of material through a nozzle to build structures layer by layer	- Suitable for large scale construction - Compatible with wide range of soil-based mixes - Relatively simple hardware - High material efficiency	- Requires careful control of rheology of the mix - Limited resolution - Potential anisotropy at layer interface	[49,50]
Binder jetting	Selective deposition of liquid binder onto layers of powdered soil or sand	- Enables complex geometries - High geometric accuracy	- Limited scalability - Requires post processing - Binder selection impacts sustainability - complexity in handling powdered material	[20,51]
Material jetting	Deposition of droplets of lo viscosity material through a printhead onto a build platform	- High precision - Good control of material placement	- Limited by material viscosity - Not suitable for coarse or fibre reinforced soils	[52]
Powder bed fusion	Use of thermal energy to sinter or fuse powdered material layer by layer	- No binders required - Potential for extra terrestrial applications	- High energy requirement - Unsuitable for wet soil - Limited build size	[53]

utilises printheads mounted on frames, robotic arms, or cranes. 46 studies out of the reviewed 49 studies (93.9%) have employed material extrusion technology; hence, in-depth analysis will be focused on material extrusion.

(2) Binder jetting: an additive manufacturing process that involves the deposition of a liquid binder onto layers of powdered material to create complex structures [49]. This technology has shown significant potential in the fabrication of ceramic parts and is advantageous for creating complex shapes [20,51].

(3) Material Jetting: droplets of build material are selectively deposited from a print head onto a build platform [52]. This technology is widely used in the fabrication of printed electronics [49]. The range of materials that can be used in material jetting is currently limited by viscosity and rheological properties of the ink, restricting its application to large-scale construction applications [52].

(4) Powder bed fusion: thermal energy selectively fuses regions of a powder bed to melt or sinter a layer of powdered material, fusing it together to form a solid part. This technology is currently being investigated for potential extraterrestrial applications [53].

A comparison of all four techniques, including advantages and limitations, is summarised in Table 3. All four techniques share the fundamental principle of constructing complex structures by sequentially adding small layers of material. The process begins with the creation of a 3D computer-aided design (CAD) model, which is subsequently divided into multiple 2D layers. These layers are then incrementally printed using the designated material, ultimately producing the desired prototype as specified in the CAD model. Provided the distinct characteristics of each technology, including the materials used and the size of construction elements, 3D printing techniques in the construction industry predominantly rely on extrusion-based techniques and binder/material jetting processes. Among the 49 publications reviewed, only 2 (4.1%) specifically address binder jetting [1,20,51] (2%) address material jetting [52].

4.2. *Current soil-based 3D printing systems*

An early pioneer in 3D printing with soil was the Italian company WASP (i.e., World's Advanced Saving Project), which also created a specialised bio-composite to enhance the stabilisation of soil mixes [18]. Reviewed studies have utilised different 3D printers, nozzle systems and pumping mechanisms for soil mixes. The sub sections provide information on these technologies.

4.2.1. *3D soil printers*

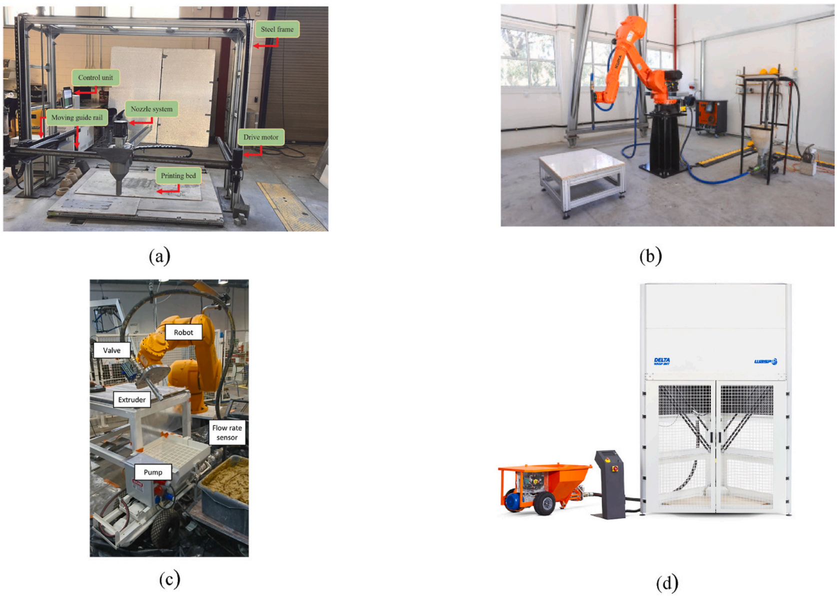
Extrusion based 3D soil printers utilise various printheads mounted on different structural systems. These mounting systems significantly influence the printability, scalability, and application of soil-based printing in the construction domain. Based on their mounting mechanisms, soil 3D printers can be categorised into three primary types: Gantry based system, robotic arm-based system, and cable driven systems. Each of these configurations has unique advantages and limitations, as summarised in Table 4.

Gantry-based 3D printing systems operate on a rigid frame with movement along the X, Y, and Z axes, similar to conventional Cartesian 3D printers [13,26,28,44]. These systems are widely used in laboratory settings and controlled environments due to their high precision and structured print workspace. For instance, Bhusal et al. [28] used gantry-type printer with a steel frame measuring 2 m × 2 m × 2 m for the printing process (Fig. 5 (a)). Similarly, Zavaleta et al. [14] also used a Colibri 3D-e series gantry printer prototype, developed at PUCP, comprising of four main subsystems: movable, supporting, controlling, and feeding. Additionally, Maierdan et al. [15] explored a syringe-based gantry printer, particularly suited for high-viscosity materials requiring specific flow control. Nonetheless, the major disadvantage of gantry-style printers includes fixed print areas, limited mobility, and challenges in scaling up for large structures.

On the other hand, robotic arm-based 3D printers provide multi-axis movement, that facilitates greater flexibility to print complex geometries as well as function effectively in diverse terrains [22,24,25,27,40,54,55]. These systems are particularly beneficial for large-scale applications but are constrained by limited reach, complex programming requirements, and lower structural stability compared to gantry systems. Several researchers have utilised robotic arm setups for printing earth-based mixtures. Robotic arm setup is a common printer setup employed to print soil-based mixes. Asaf et al. [22] used a robotic cell for 3D printing clayey soil,

Table 4
Advantages and limitations of 3D printers and mounting systems.

Mounting mechanism	Structure	Advantage	Limitations	Reference
Gantry based	A rigid frame with three-axis (X, Y, Z) movement, similar to Cartesian 3D printers.	High precision, good for small to medium-scale printing, commonly used in laboratory settings and controlled environments.	- Limited print area - Fixed workspace - Mobility issues	[13,26,28,44]
Robotic arm	A multi-axis robotic arm equipped with an extruder.	High flexibility, suitable for complex geometries and large-scale printing, adaptable to different terrains.	- Limited reach - Complex programming - Lower structural stability	[22,24,25,27,40,54,55]
Cable driven	Print head suspended by cables connected to multiple anchor points.	Large-scale capability, adaptable to different locations, ideal for field printing.	- Lower precision - Requires careful tension control	[56,57]



(a) (b)

(c) (d)

Fig. 5. Printers are used for printing soil-based mixes. (a) Gantry-type printer [28], (b) Robotic cell with an industrial robotic arm, a mortar pump and a concrete vibrator [22], (c) Staübli Robotics printer [39] and (d) Delta WASP 3 MT Printer [58].

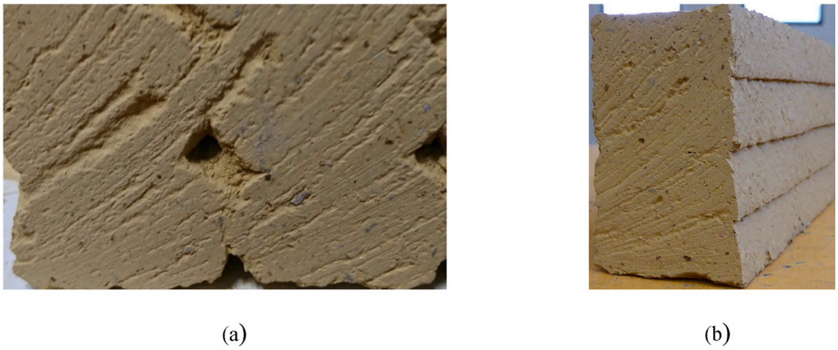
incorporating a KUKA KR50R2100 industrial Robotic arm with a payload capacity of 50 kg and a radial reach of 2100 mm, as shown in Fig. 5(b). Similarly, Perrot et al. [39] employed a six-axis industrial robotic arm printer designed by Staübli Robotics, integrated with an electric pump (Fig. 5(c)).

Cable-driven 3D printers that rely on a printhead suspended by cables, attached to multiple anchor points. This system enables large-scale printing over variable locations, making it suitable for field-based applications. Even though some critical challenges remain in terms of structural stability and deposition accuracy, significant efforts have been made to enhance the printing system with sensors that, for example, allow it to avoid collisions with the printed structures and the suspended moving cables [57], making this technology more suitable for large-scale soil-based structures.

As already mentioned, one of the pioneering companies in the production of 3D printers for soil-based printing is the Italian WASP. 9 studies (18.4%) out of the reviewed studies have utilised it for developing novel mix designs based on soil for construction purposes. Ferretti et al. [59] utilised a printer system based on Liquid Deposition Modelling (LDM) technology, specifically designed for ceramic material extrusion. As shown in Fig. 5(d), this kinematically precise system integrates a screw extruder with a pressure sensor, ensuring accurate material flow control. Additionally, the continuous feeding system allows uninterrupted extrusion by monitoring operating pressure at the extruder hose inlet, ensuring homogeneity and workability of the soil mixture. Rückrich et al. [19,22] also utilised a similar printer system to that used by Ferretti et al. [50], featuring a screwless extruder head, which offers alternative material deposition control.

4.2.2. *Nozzles for soil-based extrusion*

The nozzle is an important part of material extrusion-based 3D printing, acting as a medium through which the material is precisely extruded. In addition to its basic function, the nozzle addresses certain challenges in 3D printing, such as controlling flow consistency,



(a) (b)

Fig. 6. Cut section of printed samples of earth: (a) printed with circular nozzle and (b) printed with rectangular nozzle [39].

(a) (b)

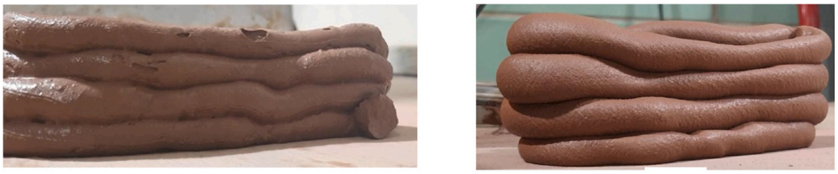
Fig. 7. Nozzle design displayed as (a) sectional drawing and (b) mounting with spool holder [63].

managing material viscosity, and ensuring uniform deposition. It plays an important role in reducing air pockets and cold joints while adapting to various geometries. By directly influencing layer adhesion, surface quality, and structural integrity, the nozzle becomes a important component in optimising both the efficiency and quality of 3D-printed structures.

For soil-based materials, nozzle shapes used in literature generally fall into two categories: rounded or elliptical [22,59], and rectangular or square [39,60]. Rounded or elliptical nozzles usually provide smoother extrusion, reducing surface roughness and contour deviation, while rectangular or squared nozzles improve layer compression and structural stability with greater surface roughness and contour deviation [60], making them ideal for construction-related applications. Out of 49 studies considered, only 3 [39,42,61] have utilised rectangular or square nozzles. Quantitative assessment of deposition quality is still not consistently reported in the soil-based studies. Where it is reported, it is commonly measured using geometric deviation of the printed filament or toolpath or visual observation. Perrot et al. [39] conducted experiments using both circular (D35 mm) and rectangular (21 mm × 40 mm) cross-sectional nozzles, and deposition quality was evaluated based on cross-sectional observations of printed elements. The findings revealed macro voids in circular die extrusions, whereas rectangular die provided a closed form structure with only micro voids, as depicted in Fig. 6. This observation highlights the importance of selecting appropriate nozzle geometries for specific type of applications.

Nozzle size is also an important aspect in 3D printing, that requires precise consideration to meet specific operational requirements. Chan et al. [21] highlighted that the nozzle size is one of the factors that significantly influence the quality, speed, material consumption, and precision of printed components. The study showed that larger nozzles, when paired with optimised pressure and speed parameters, facilitated faster printing and lower surface roughness. Conversely, smaller nozzles allowed for higher precision and material efficiency but increased the printing time. Larger nozzles also proved to achieve high-quality prints when provided with appropriate printing pressures and speeds [21]. In soil based printable mixes, printing speed is generally expressed as the nozzle travel speed (mm/s), and pumpability/extrudability is often evaluated by continuous extrusion stability and dimensional consistency of the extruded filament. Further analysis illustrates the diverse nozzle sizes used in 3D printing for soil and clay-based materials, highlighting their varying impacts on performance. A 30 mm nozzle, as used by Ferretti et al. [59], was shown to enhance printing speed and promote consistent deposition in fibre-reinforced clay mixes. However, fibre incorporation was found to increase surface roughness and limit geometric precision. Similarly, the use of a 25 mm nozzle by Zavaleta et al. [14] improved buildability, but challenges were reported in achieving smooth surface finishes, requiring additional mix optimisation to balance flow and cohesion. Another study by Bhusal et al. [28] reported that 20 mm nozzles facilitated higher printing speeds but increased the risk of shrinkage cracking during drying in the absence of fibre reinforcement. In contrast, intermediate nozzle sizes of 12.5–15 mm, as employed by Asaf et al. [22] and Rückrich et al. [23,62], were found to improve pumping stability and produce more uniform layers. Studies have also used nozzle diameters as small as 2.4 mm [2,13] [mm [15], reporting enhanced accuracy and reduced material consumption but significant challenges with extrusion pressure, frequent blockage, and limited scalability for larger elements. These findings highlight that nozzle size selection is not an independent parameter but a fundamental trade-off between speed, surface quality, and layer cohesion. Larger nozzles improve extrusion and structural buildability but often compromise precision, while smaller nozzles enhance detail at the cost of print stability and scalability. Therefore, application-based optimisation is essential for soil-based extrusion systems.

A study by Jauk et al. [63] introduced customised nozzles to improve the printing process for filament-reinforced clay objects. These nozzles were equipped with a filament-guiding mechanism that centres the filament within the extrusion channel, thereby ensuring consistent material application. The design features a threaded base for secure attachment to the extruder, a smaller inner nozzle to guide the filament, and a larger outer nozzle that shapes the extruded clay (as Fig. 7). This nozzle modification is specifically engineered to integrate fibre reinforcement directly into the clay matrix during the printing process, potentially enhancing the tensile strength of the printed object by approximately 15%, regardless of the fibre type used. This development proves that strategic adjustments to nozzle design can improve the mechanical properties of 3D-printed clay objects, highlighting the critical role of design innovations in advancing 3D printing techniques.



(a) (b)

Fig. 8. Cob Mixture Printed using (a) manual pump and (b) electric pumps [25].

4.2.3. Pumping and extrusion

The fabric of soil, a major factor influencing the hydro-mechanical behaviour of the soil, is strongly controlled by the printing process. The pumping system is responsible for moving the printing material through the nozzle onto the build platform, while extrusion refers to the actual deposition of material onto the build platform. The performance of the pumping and extrusion system is necessary for ensuring consistent and continuous deposition, which is particularly challenging when using soil-based materials for printing.

Zavaleta et al. [14] studied the pumpability of soil mixes using the MAI®2PUMP-PICTOR pump, which allowed for continuous extrusion of filaments at flow rates ranging from 1.5 to 8.5 L/min. It was found that the composite materials could not be extruded when the pump working pressure exceeded 15 bar. This observation indicates the importance of controlling pump pressure and flow rate to avoid clogging and ensure a smooth and continuous extrusion process. Similarly, El Aabbas et al. [17] used a mechanical piston system to push material through a pipe, which allowed for precise control of the extrusion process. This precision is vital for achieving high-quality prints with consistent material deposition and minimal defects.

Moreover, Alqaneeh et al. [25] and Bai et al. [64] established that the printability of soil mixes is primarily influenced by two factors: the extrusion system and the fluidity of the mix. For instance, Alqaneeh et al.'s [25] study showed that materials extruded using a manually operated system appeared moister than those extruded with an electrically operated system as depicted in Fig. 8, despite being made from the same batch. This difference was attributed to the extrusion process, as electrically driven systems impose higher shear stresses and greater friction within the extrusion mechanism and delivery hose, which promotes moisture loss during material transport and deposition [25]. In contrast, manual extrusion involves lower extrusion pressures and shorter extrusion times, helping to preserve the moisture [25]. This finding highlights the role of the extrusion system in determining the final properties of printed components, in terms of moisture content and consistency during the printing process. An important aspect that could lead to blockage during pumping or extrusion was investigated by Perrot et al. [65] for cementitious materials and also holds true for soil extrusion. In this study, a criterion formulated by Wroth and Houlsby [66] expressed in Equation [1] was used.

$$\frac{t}{H^2/c_v} < 0. \quad [1]$$

It suggests that, in order to avoid clogging of the extruder system, the time needed for the extrusion t should be an order of magnitude smaller than the consolidation characteristics time H^2/c_v, where H is the length of the extrusion path and c_v the coefficient of consolidation according to Terzaghi's theory. In this case, when soil with a high sand-to-clay ratio is used, the extrusion velocity should be set according to the mentioned criterion.

Another factor influencing the extrusion process is the plasticity index of a mixture, which determines the pumpability and extrudability during the 3D printing process. Rückrich et al. [23] evaluated the cohesiveness of earth mixtures using the plasticity index and found that a higher plasticity index results in better cohesiveness, which in turn improves pumpability and extrudability. This finding shows the importance of modifying the material properties, such as plasticity, to suit the specific requirements of 3D printing.

While increasing the clay content can improve plasticity, in turn increasing the pumpability, it also raises concerns about potential shrinkage [39]. Shrinkage can lead to cracks and structural weaknesses in printed objects, particularly in large-scale construction. Therefore, understanding the relationship between extrusion and shrinkage is critical for optimising the printability and structural integrity of soil-based materials. However, interestingly Ferrari et al. [59] reported that the extrusion process has negligible effects on the shrinkage behaviour of soil mixes.

The advancements in extrusion systems, such as dual-ram extruders and mechanical pistons, provide significant improvements in the printability of soil-based materials. These innovations enhance the performance of the pumping and extrusion systems, enhancing the extrusion rate, continuity, consistency, and mobility, making them more suitable for the large-scale application of 3D printing in construction [40]. However, despite these advancements, the extrusion of soil-based materials remains a challenge, particularly in terms of controlling moisture content, shrinkage, and material consistency. Further research is needed to optimise extrusion systems for specific soil mixes, focusing on the development of more efficient systems that can handle the unique challenges posed by these materials.

4.3. 3D printable mixtures

As discussed, printability is a critical factor in the development of 3D printable soil-based mixes, incorporating aspects such as extrudability, buildability, and flowability, which are dependent on the composition of the mixes and rheological properties. Soil alone does not have sufficient mechanical properties and drying behaviour required for construction purposes and sometimes might lack the required rheological properties required for extrudability and flowability. Hence, Section 4.3.1 analyses how soil type, water content, and stabilisers are modified to improve printability, Section 4.3.2 discusses how the resulting fresh state behaviour is quantified in terms of rheology and Section 4.3.3 focuses on the fresh state strength development for constructability.

4.3.1. Material composition

Clay and sand are the primary constituents of 3D-printable soil mixes, with their proportions directly influencing printability. A study by Rückrich et al. [23] highlighted the importance of clay type and composition, noting that different clays exhibit varying flow properties. They recommended a 1:2 clay-to-sand ratio for mixtures with high illite and kaolinite content, whereas a 1:1 ratio was suggested for smectite-rich clays to achieve optimal strength. The particle size and mineralogical composition of clays also play a crucial role in determining water demand, workability, and shrinkage. Furthermore, Bhusal et al. [28] found that a high nontronite clay content (15%) led to excessive shrinkage (ASTM C490 [28,67]) and cracking, indicating the need for additional stabilisers or fibre reinforcements.

Unlike traditional soil construction methods, where moisture content is optimised for maximum dry density in 3D printing, it must be evaluated based on process performance to balance flow properties and material rigidity. Achieving this balance is essential for gaining the desired plasticity required for printing [22]. In the study by Asaf et al. [22] a correlation coefficient of −0.81 was reported between mix rigidity and the clay-to-water ratio, whereby an increase in water content was associated with a reduction in particle friction and a consequent decrease in overall material rigidity.

Consequently, water content governs both extrudability and buildability. Too much water reduces structural stability, while too little causes flowability issues. Several studies tried to optimise water content based on soil compositions, as summarised in Table 5. For instance, Gomaa et al. [40] recommended a 23–25% water content for improving extrusion consistency in soil consisting of 15-25% clay and 75-85% sand reinforced with fibre. Alqenaee and Memari [25] proposed a mix of 49% clay, 24.2% water, 15.3% sand, 10% lime, and 1.5% straw for achieving a balance between flow and strength. Perrot et al. [39] study developed a high-water-content (45%) clay mix with quartz, kaolinite, illite, and smectite, optimised with alginate for better cohesion. Almost all the studies relied on trial-and-error method to determine the initial water content, a process that is expensive in both time and materials and may not always be feasible for excavated earth or raw soil. Accordingly, correlating mix behaviour with known soil mechanics parameters, such as consistency limits [68], is important for the effective characterisation of soils intended for 3D printing. The primary challenge in developing a printable mix for 3D printing lies in designing a thixotropic mix that can be extruded seamlessly during the printing process while maintaining its structural integrity after deposition [69]. The key rheological requirement for developing such a mix is discussed in detail in section 4.3.2, while the practical challenges related to selecting and maintaining an appropriate water content during printing are discussed further in Section 5.2.

Stabilisers are often incorporated to improve mechanical strength, reduce shrinkage, and enhance printability of soil mixes, in part by modifying water demand and retention and by adjusting fresh state flow properties. Hydrated lime is widely used to reduce water absorption and improve durability. Alqenaee et al. [25] observed that mixes with higher lime content appeared more moist, suggesting that lime modifies the water retention behaviour of the soil. Nevertheless, Bhattacherjee et al. [72], based on their review of the literature on concrete 3DP, suggest that incorporating limestone into a 3D printable mix can improve its printability, as indicated by the larger spread diameter observed in the slump test. However, they also note that adding ultra-fine limestone may decrease the workability of the mix, likely due to increased water absorption and heightened friction between the particles. Similarly, it was reported that the inclusion of natural pozzolana did not significantly enhance printability or prevent shrinkage in some cases [28]. These observations provide a rationale for evaluating alternative binders and bio-based additives when conventional stabilisers do not deliver consistent results.

Accordingly, silicone-based binders have been explored as an alternative stabiliser in previous studies, with Bar-Sinai et al. [73] using a desert soil-silicone mix to improve cohesion and printability. Sodium alginate has been found to increase electrostatic interactions in kaolinite suspensions, leading to improved flow characteristics [15]. Furthermore, potato starch gel has been investigated as a biodegradable stabiliser; when combined with sisal fibres, improved control of shrinkage and cracking during hardening was observed [44]. These results indicate that polymer characteristics and soil mineralogy should be optimised to achieve stable extrusion and layer integrity.

In addition to stabilisers, natural fibres also play a critical role in reducing shrinkage and cracking in 3D-printed soil structures. Bhusal et al. [28] found that incorporation of chopped wheat straw fibres (1.5% by dry weight, fibre length less than 20 mm) significantly reduced shrinkage to as low as 2.6%, making them an important component for improving dimensional stability (Dimensional stability was assessed through axial drying shrinkage measurements following ASTM C490 [67] along with crack width observation in both casted and 3D printed specimens). Previous studies [13,40,44,74] have investigated the incorporation of different types of fibres. For instance, straw fibres (2%) were used by Gomaa et al. [40], which resulted in improved extrusion stability, the associated rheological enhancements are discussed in detail in Section 4.3.2. The optimal formulation identified in Zavaleta et al.'s [14] study consisted of a 3.0% (weight/volume) chitosan aqueous solution mixed with 71% soil and 1% sisal fibres, derived from the *Agave sisalana* plant by weight. The incorporation of chitosan and sisal fibres helped improve the water resistance of the mix, making it more suitable for various environmental conditions [14]. Ferretti et al. [74] found that incorporating rice husk fibres proved to reduce

Table 5
Mix compositions utilised in the reviewed studies.

Author	Year	Soil used (Soil location/ source)	Liquid limit (LL) %	Plastic limit (PL) %	Plasticity index (PI) %	Soil composition	Water content (WC) %	Additives	Reference
Asaf et al.	2023	Quartz dune sand (Kfar Giladi Minerals)	-	-	-	Quartz – 99.9%, Calcite – 0.1%	15.1 - 18.2	-	[22]
		White kaolinite clay/White (Alco chemicals)	-	-	-	Kaolinite – 99.4%, Quartz – 0.4%, Muscovite – 0.2%			
		Brown kaolinite clay/ Chocolate (Yehu Clays Ltd)	-	-	-	Kaolinite – 76.8%, Quartz – 12.7%, Calcite – 1.4%, Ivsite – 3.9%, Picromite – 3.1%, Orthoclase – 2.1%			
		Marl clay/ Mamshit (Yehu Clays Ltd)	-	-	-	Kaolinite – 41.5%, Quartz – 17%, Calcite – 22.9%, Illite – 7.0%, Muscovite – 5.0%, Orthoclase – 6.2%			
Rückrich et al.	2024	White – blue ball clay/ Clay K	70.6	39.2	31.4	Kaolinite – 66.4%, illite – 27.2%, Microline – 4.7%, Quartz – 1.6%	15 - 20	-	[23]
		Grey-blue ball clay/ Clay I	91.0	49.2	41.8	Illite – 49.5%, Kaolinite – 18.2%, Quartz – 32.5%	15 - 22		
		Moza clay/ Clay M (Judean mountains)	129.9	71.7	58.9	Kaolinite – 5%, Montmorillonite – 60%, Dolomite, Calcite – 25%, Iron Oxide – 4%, Organic Substance – 1%, Gypsum, Salt, Quartz	16 - 23		
		Local clay/ Clay L (Israel)	56.7	26.3	30.4	Calcite – 63.5%, Kaolinite – 7%, Illite – 8%, Montmorillonite – 1.2%, Dolomite – 5%, Quartz – 13.3%, Payroskite – 2%	14- 18		
Bhusal et al.	2023	Well graded sand/S6 (Belen)	33.6	19.9	13.7	Kaolinite – 49.3%, Nontronite – 14.6%, Illite – 36.1%	38- 43	Hydrated Lime (2), Natural Pozzolana (4%), Natural Fibres (1.5%) (wheat straw fibre)	[28]
Zavaleta et al.	2024	Quarry soil (Peru)	27	16.2	10.8		24 - 31	Chitosan (1%-3%) and Sisal Fibres (1%)	[14]
El Aabbas et al.	2024	Clay (Morocco)	58	24	34	Quartz, Kaolinite, Calcite, Illite	31- 35	-	[17]
Perrot et al.	2018	Raw earth (Ille et Vilaine, France)	48	27	21	Quartz, Kaolinite, Illite, Smectite	45	Commercial Alginate (3%)	[39]
Ferreti et al.	2022	Silty clay soil (Massa Lombarda, Italy)	-	-	-	-		Lime based binder (8%) and Rice Husk (1.41%), Silica Sand (18.78%)	[59]
Curth et al.	2024	Sandy clay loam (Montecito mud)	44	15	29	-	20	Wheat straw (5%-25%)	[27]
Daher et al.	2023	Excavated soil (France)	18.7	11.8	6.8	-	40	Ordinary portland cement, superplasticizer (modified phosphonate, polymer, polycaarboxylate)	[70]
Silva et al.	2022	Low plasticity	27	16.2	10.8	Quartz, Illite, Kaolinite	19-27	Starch gel (0%-5%), sisal fiber (1%)	[44]

(continued on next page)

Table 5 (*continued*)

Author	Year	Soil used (Soil location/ source)	Liquid limit (LL) %	Plastic limit (PL) %	Plasticity index (PI) %	Soil composition	Water content (WC) %	Additives	Reference
Faleschini et al.	2023	sandy clay (Peru) Low plasticity, well-graded silty clay (Italy)	22	16	6	-	20, 24	Sand (18.78%-22.78%), gravel (2.96%), Rice husk (0%-1.41%), Bottom ash (0%-2.75%), Marble dust (0%-2.75%), hydrated lime (0%-11%), Cement (0%-11%), fiber (0.5%)	[71]

linear shrinkage and improve mechanical behaviour, while shredded rice husk fibres improved long-term mechanical properties through natural mineralisation processes [74].

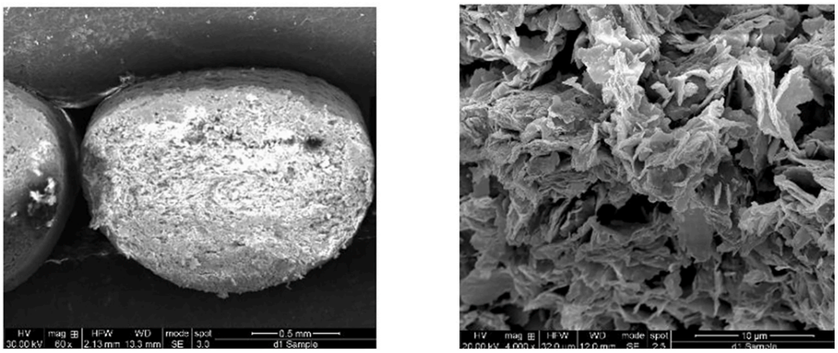
Beyond the influence of additives on shrinkage, strength and fresh state behaviour, material composition also controls the process induced microstructure created during extrusion and layer wise deposition. Microstructural investigations on printed soils have shown that the printing reorganises particles and pores, producing an anisotropic fabric that differs from conventionally cast or compacted soil. Ferrari et al. [75] used scanning electron microscopy and mercury intrusion porosimetry to demonstrate that clay rich printable soils develop a dual pore structure during printing. Finer intra-pores developed were governed by soil mineralogy, and water adsorption and larger inter filament macro pores were generated by the relative positioning and deformation of adjacent filaments during deposition, as shown in Fig. 9. The extent of these macropores is strongly influenced by material cohesion, water content and soil type, with high plastic soils promoting better filament fusion and reduced interlayer voids. This proves that the printing interface is not just a geometric boundary but a microstructurally distinct zone, the quality of which depends on the moisture state, thixotropic rebuilding and the time taken between successive layer deposition.

At a structural scale, Hong et al. [76] showed that strain localisation and damage in printed soil elements tend to initiate at interlayer regions, indicating that interface quality governs mechanical response. Similarly, studies on granular and soil structure interface using 3D-printed geometries have shown that surface roughness and particle morphology strongly control shear resistance and bonding behaviour [77]. Structural build up during drying further modifies the printed fabric, where Motamedi et al. [78] show that rapid moisture loss leads to weak interlayer bonding and microcracking, whereas controlled drying promotes progressive interparticle bonding across layers. Nevertheless, quantitative analysis relating soil type and stabilisation strategy to interlayer microstructure and bonding performance remains limited in the domain of soil 3D printing.

4.3.2. Rheological properties

Rheological properties play an important role in determining the printability of soil-based 3D printing materials, influencing their extrudability, buildability, and overall structural integrity [22,79]. Unlike cement-based materials that rely on hydration reactions for setting and strength development, rheological behaviours of soil mixes are predominantly controlled by moisture content, particle distribution, and stabilising additives. Therefore, tailored rheological assessments are required to ensure these materials meet the performance criteria required for 3D printing applications.

The basic rheological parameters that govern printability include yield stress, which controls the material's flow during pumping and its stability post-extrusion; viscosity, which defines resistance to deformation under applied stress and influences pumping efficiency and layer adhesion; and thixotropy, which determines how quickly the material regains strength after extrusion to support



(a) (b)

Fig. 9. SEM vertical cross sections of 3D printed soil [75]. Magnifications are (a)300× and (b) 4000X.

subsequent layers [15]. These properties require careful balance to achieve successful printing [39]. The mix should exhibit a sufficiently low dynamic yield stress to enable smooth extrusion through the nozzle, while rapidly developing a higher static yield stress after deposition to ensure structural integrity [80].

Out of the 49 reviewed studies, 18 (36.7%) have attempted to quantify the fresh-state behaviour of soil-based printable mixtures through rheological measurements. Table 6 summarises the list of tests and pros and cons related to each test carried out in the reviewed studies. Rotational rheometers have been widely used for measuring static and dynamic yield stress, viscosity, and thixotropic behaviour, providing comprehensive flow curve analysis [22,28,39]. Asaf et al. [22] used a rotational rheometer to highlight the necessity of balancing thixotropy and dynamic rheology to ensure smooth pumping while maintaining layer stability. Nevertheless, rotational rheometers may not effectively shear very stiff soil mixes. Other methods, such as the cone penetration test, have been applied to evaluate the workability and flow behaviour of fibre-stabilised soil mixes, as reported in the studies of Ji et al. [26] and Zavaleta et al. [14]. The flow table test (ASTM C230 [81]), which measures flowability by evaluating material spread, has proven useful in correlating rigidity of the material with extrusion rates, as confirmed by statistical analysis carried out by Asaf et al. [22] on different clay mixtures.

While these experimental procedures provide useful indicators of fresh state behaviour of 3D printable mixes, the meaningful interpretation and comparison of the resulting rheological parameters further depend on the constitutive rheological model used to describe the material response. In studies related to extrusion-based 3D printing, rheological responses are commonly interpreted using simplified models such as the Bingham or Herschel–Bulkley models, which describe materials exhibiting a yield stress followed by shear-dependent flow behaviour [65,86]. These models are widely applied in concrete 3D printing to extract parameters such as static and dynamic yield stress and plastic viscosity from flow curves [87]. For soil-based 3D printing materials, however, the application and reporting of rheological models remains limited. Many studies report yield stress values derived from penetration or vane shear tests without fitting a specific flow model, while others extract apparent viscosity values from rotational rheometer measurements without formally identifying the governing constitutive relationship [14,26,70]. This is partly due to the complex, heterogeneous, and often fibre-reinforced nature of soil-based mixtures, which may exhibit non-linear, shear-thinning behaviour that is not adequately captured by simple Bingham assumptions. Where rotational rheometers are utilised, Herschel–Bulkley or power-law type behaviour is often assumed, particularly for clay-rich or polymer-stabilised soil suspensions [22,28,39]. However, differences in

Table 6

Comparison of rheological test methods used in soil 3DP.

Rheological testing method	Description	Measurable rheological parameters	Pros & Cons	Reference
Flow table test	A brass conical mould is placed at the table centre and filled with the mixture. The mould is then removed, and the table is jolted 25 times, and the spread of the material is recorded. (ASTM C230 [81])	-	- Cannot achieve any rheological parameters	[22,28]
Rotational rheometers	Once the material is thoroughly mixed, the fresh mix is poured into a cylindrical mould and subjected to shear using a rheometer with a shear vane spindle (shear rate is increased (0/s to 100/s in 60s) and gradually decreased (100/s to 0/s in other 60s) (ASTM C1749/ASTM C1702 [82])	- Static yield stress - Dynamic yield stress - Apparent coefficient of viscosity - Structural buildup rate (A_{thix})	- Fully automated and easy to do - Full flow curves can be achieved - Can use single batches to conduct the yield stress measurement with time - Can easily achieve the rheological parameters. - Expensive	[22,28,39]
Modified flow table test	A cylindrical mould (45 mm diameter and height) is filled with material, which is then manually extruded to form a cylindrical sample. The sample is placed on a wooden plate, and each side of the plate is alternately lifted to the sample's height (45 mm) before being dropped onto the surface beneath it. This process is repeated 10 times. The spread of the material is measured with a calliper or spacer, with a larger spread indicating greater flowability. $flow(\%) = \frac{spread\ dia - sample\ base\ dia}{sample\ base\ dia} \times 100$	-	- Cannot achieve any rheological parameters	[23,62]
Triangular bag test	The material is manually extruded through an opening in a triangular bag, simulating the pumping and extrusion process used in 3D printing.	-	- Easy to do and reliable assessment of a material's printability for a given composition and applied force	[23,62]
Cone penetration test	cone is released to fall from a specified distance onto a cylindrical sample (ISO 17892-6 [83])	- Yield stress - A_{thix}	- Fully automated in some instances - Can be used as a onsite method - Easy sample preparation due to the small sample size used - Cannot achieve any flow curves	[14,23]
Vane shear test	Similar test procedure to the rotational rheometer but uses lower rotational speeds and can be manually operated (ASTM D4648 [84])	- Yield stress - A_{thix}	- In situ test method - Ability to use a single batch for multiple measurements - Cannot achieve the flow curve	[85]

shear rate ranges, pre-shearing protocols, and data fitting procedures lead to significant variability in reported rheological parameters, limiting direct comparison between studies. The lack of consistent reporting of the adopted rheological model further complicates the interpretation of yield stress, viscosity, and thixotropy values across studies.

A comparative analysis of rheological test results (Table 7) from the reviewed studies highlight considerable variations in yield stress, viscosity, and thixotropy depending on soil composition and stabilisation methods. For example, clay-sand mixes studied by Asaf et al. [22] showed a static yield stress of 1-2 kPa and a dynamic yield stress of 1 kPa, with a plastic viscosity of 50 Pa s, indicating moderate flowability while maintaining some degree of structural buildup. In contrast, well-graded sand stabilised with lime, as tested by Bhusal et al. [28] using a Brookfield rheometer, exhibited significantly higher static yield stress values ranging from 1.17 to 2.58 kPa, with dynamic yield stress as low as 0.08 kPa. This suggests that lime stabilisation enhances structural buildup while maintaining extrudability. The study also reported plastic viscosities ranging from 2.8 to 8.3 Pa s, reflecting variations in flow resistance based on lime and fibre additions. Predominantly, the thixotropy index of these materials varied widely, with values as high as 32,766 Pa/s, emphasising the role of additives in improving structural stability. It can be observed from Table 6 that static yield stress is the most frequently reported rheological parameter in soil-based 3D printing studies, whereas dynamic yield stress, plastic viscosity and thixotropy are often not reported. This trend can be attributed to several factors such as static yield stress, which is closely related to conventional geotechnical parameters (i.e. undrained shear strength and penetration resistance) and can be easily determined using simple and widely used tests, including cone penetration vane shear methods. These tests are particularly designed for stiff, heterogeneous and fibre reinforced soil mixes, for which reliable flow curves and viscosity measurements using rotational rheometers are difficult to obtain. Moreover, dynamic rheological parameters such as plastic viscosity and thixotropy require specialised equipment, carefully controlled shear histories and standardised testing protocols, which are not readily available for soil based printable materials (Table 5). As a result, many studies prioritise static yield stress measurement as a practical indicator for printability.

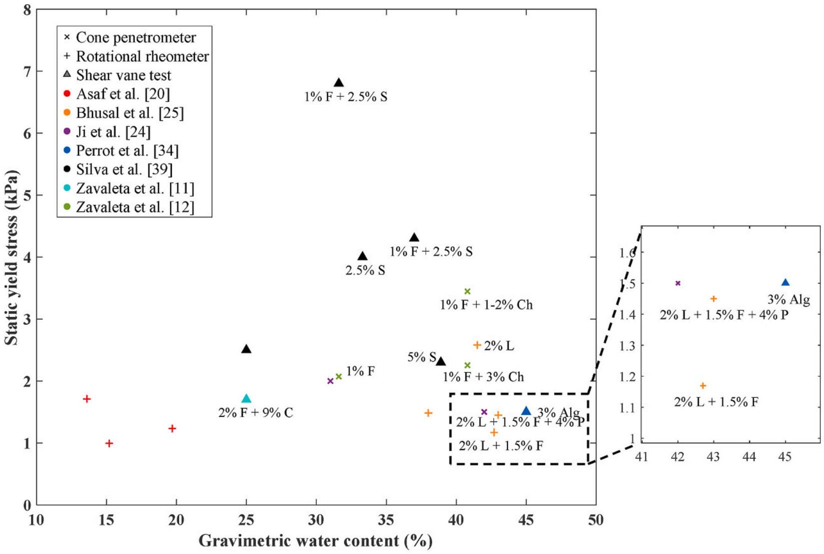
The impact of soil composition on rheological properties is particularly evident when considering particle size distribution and mineral content. Analysed studies have shown that an increase in kaolinite content enhances thixotropic behaviour, improving the material's ability to regain structural integrity after extrusion [22]. Perrot et al. [39] explored the use of alginate biopolymers to induce thixotropic effects in soil-based mixtures, demonstrating improved buildability through penetrometer tests. Similarly, Silva et al. [44] utilised shear vane tests to analyse the fresh-state behaviour of soil stabilised with potato starch gel, finding that a 2.5% starch gel addition resulted in a yield stress of 6.8 kPa, significantly enhancing printability. The balance between flowability and buildability is crucial in ensuring the successful deposition of layers without deformation. The trade-off between material deposition speed and construction speed further complicates this process, as the setting of the material must begin as soon as possible to support the increasing load induced by subsequent layers.

Fig. 10 illustrates the trend of static yield stress with respect to the gravimetric water content of printable mixes as reported in the reviewed studies. Marker shape denotes the test methods (× cone penetrometer; + vane shear; ▲ rotational rheometer) and point

Table 7

Rheological properties of soil-based 3D printing mixtures.

Soil type	Author	Testing apparatus	Yield stress (kPa)		Plastic viscosity (Pa.s)	Thixotropy (Pa/s)	Reference
			Static	Dynamic			
Clay sand mix	Asaf et al.	Rotational Rheometer ICAR Plus	1-2	1	50	-	[22]
Raw earth (Fine soil) with alginate	Perrot et al.	Anton Paar Rheolab QC vane shear device	1.5	-	-	-	[39]
Well graded sand	Bhusal et al.	Brookfield rheometer	1.49	0.35	4.1	11132.5	[28]
Well graded sand stabilised with lime			2.58	0.08	8.3	32766	
Well graded sand stabilised with lime, fibre			1.17	0.29	2.8	268.8	
Well graded sand stabilised with lime, fibre and pozzolana			1.45	0.18	3.8	24182.8	
Soil stabilised with fibre	Zavaleta et al.	Cone penetrometer	2.07-3.18	-	-	-	[14]
soil stabilised with chitosan and fibre			2.25-9.01	-	-	-	
Soil stabilised with fibre	Ji et al.	Cone penetrometer	1.5 - 2	-	-	-	[26]
sandy silt soil mixed with cement and superplasticiser	Daher et al.	Fall cone test	0.6-1	-	-	-	[70]
soil	Silva et al.	Humboldt vane shear	2.5	-	-	-	[44]
Soil stabilised with potato starch gel (2.5%)			4	-	-	-	
Soil stabilised with potato starch gel (2.5%) and sisal fibres (24)			6.8	-	-	-	
Soil stabilised with potato starch gel (5%)			2.3	-	-	-	
Soil stabilised with potato starch gel (2.5%) and sisal fibres (27)			4.3	-	-	-	
Raw soil stabilised with ordinary Portland cement, rice husk	Zavaleta et al.	Shear vane Test	1.7	-	-	-	[13]



F – Fibre, C – Cement, S – Starch gel, Ch – Chitosan, Alg – Alginate, P – Pozzolana, L - Lime

Fig. 10. Static yield stress vs water content variation (*data compiled from different studies and testing methods; values are shown for qualitative comparison only).

colour identifies the source (red Asaf et al. [22]; orange Bhusal et al. [28]; purple Ji et al. [26]; dark blue Perrot et al. [39]; black Silva et al. [44]; light blue Zavaleta et al. [13]; green Zavaleta et al. [14]) with text labels indicating the additives and respective dosage. It should be noted that error bars and sample size information are not specifically shown, as such data are not consistently reported in the reviewed studies, limiting quantitative comparison. Furthermore, the static yield stress values were obtained using different testing methods, which are known to probe material resistance under different stress states and shear conditions. As a result, absolute yield stress values derived from penetrometer, vane shear, and rotational rheometer tests are not directly comparable and may introduce systematic bias. Despite these limitations, an overall inverse relationship between water content and yield stress can be observed through the clusters of specific studies considered. This behaviour is expected as a higher water content in the mix results in fluid-like behaviour, resulting in less resistance to shear and vice versa. However, the magnitude and decline of yield stress with respect to increasing water content vary significantly depending on the soil type and additives.

A critical challenge in evaluating the rheology of soil-based 3D printing materials is the lack of standardised rheological testing protocols [39,44]. Unlike cement-based systems, where rheological criteria are well established, soil mixes exhibit high variability in moisture content, particle size distribution, and stabiliser interactions, making standardisation difficult. As a result, the current measurements provide only limited guidance for predicting extrudability and buildability. Optimising rheological properties is essential to advancing the use of soil in 3D printing. Achieving the right balance of yield stress, viscosity, and thixotropy ensures that the material can be efficiently pumped, smoothly extruded, and structurally stable post-deposition. Future studies should focus on developing standardised rheological testing methods tailored to soil-based mixes, exploring the influence of biopolymers and stabilisers to enhance thixotropic behaviour, and optimising water content and printing speed to improve both extrudability and buildability. By systematically controlling these parameters, researchers can refine soil-based 3D printing techniques to achieve reliable, scalable, and structurally sound printed elements.

4.3.3. Buildability

Buildability is one of the primary criteria used to evaluate the fresh state printability performance of an additively manufactured part, especially for cement and soil-based materials. This property can be assessed both qualitatively and quantitatively, through parameters such as build rate and the stability of printed layers. Critical factors influencing the buildability of 3D printed structures include the ability of the initial printed layer to support subsequent loads, the early strength development of the material, and the geometry of the printed parts [22,28,42]. These factors are important for determining how well the structure can sustain the successive deposition of layers without experiencing deformation or collapse. Despite its significance, the standardisation of buildability testing remains insufficiently developed within the field. However, several testing methods have been used in the reviewed studies. Particularly, the cylinder test [22,23,28] is the most commonly used assessment method for buildability. Some studies have also utilised the stability settlement test [22,62] and single-direction wall test [28]. These tests play a critical role in advancing the understanding of material performance during the early stages of the printing process, highlighting the need for more standardised and comprehensive testing protocols to ensure reliable results in buildability assessments.

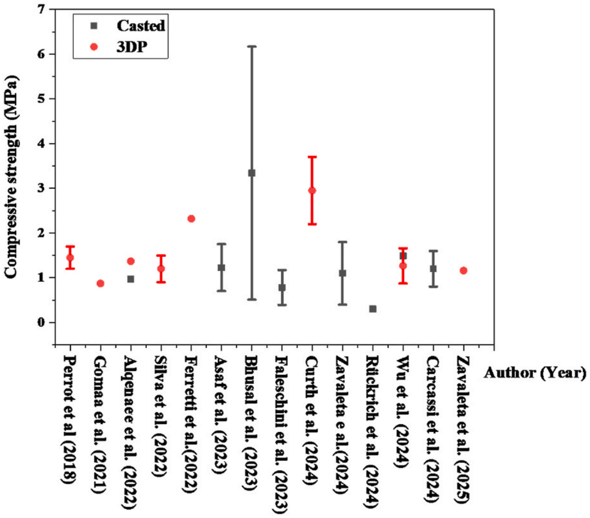


Fig. 11. Compressive strength values reported in the reviewed studies.

4.4. *Mechanical properties*

The mechanical properties of 3D printed soil structures are critical in determining the feasibility of construction applications, particularly when the printed elements are intended to function as load-bearing elements. These properties, specifically compressive strength, tensile strength, and flexural strength, are influenced by various factors such as material composition, curing conditions, printing parameters, and binder additions. The structural integrity of 3D-printed soil elements largely depends on their ability to sustain loads while maintaining stability, making the assessment of mechanical properties a key aspect of research in the construction domain.

The uniaxial compressive strength is one of the basic measures evaluating the load-bearing capacity in construction materials, with values varying based on soil composition, moisture content, additives, and printing techniques. Several of the reviewed studies have investigated this property, revealing interesting trends as illustrated in Fig. 11. Bhusal et al. [28] reported superior mechanical performance in a pure soil mixture, achieving a compressive strength of 6.17 MPa, while Rückrich et al. [23] found that montmorillonite clay minerals generally provide higher compressive strength compared to kaolinite and illite. Other modifications, such as the incorporation of chitosan, also enhanced strength development. Zavaleta et al. [14] observed that after 100 days, a mix containing 3% chitosan aqueous solution, 71% soil, and 1% sisal fibres achieved a compressive strength of 2.55 MPa, demonstrating comparable performance to conventional earthen mixtures. However, factors such as water content also play a crucial role, as shown by Alqenaee et al. [25], whose study found that when the water content exceeded 30%, compressive strength began to decline.

While the uniaxial compressive strength test (EN 12350-1 [88]) is widely adopted in the literature due to its simplicity and compatibility with printed specimen geometries, but it does not fully represent the stress conditions experienced by soil structures. Triaxial compression testing, which accounts for confining pressure, would provide a more realistic assessment of soil behaviour [89]; however, its application in soil-based 3D printing studies remains limited. This is partly due to practical challenges associated with specimen preparation and moisture control in printed materials [90], and partly due to the interdisciplinary origins of the field, with many studies emerging from architectural and structural engineering domains where uniaxial and flexural tests are more commonly employed than advanced geotechnical testing methods (Tables 1 and 2).

A comparison between 3D-printed and casted soil specimens remains difficult due to limited data availability. However, Fig. 11 illustrates that among the studies that provided both datasets [25] [91] 3D-printed specimens exhibited slightly higher compressive strength compared to casted specimens. This enhancement in strength can have resulted from the process induced fabric changes produced by the printing process (extrusion and layer wise deposition) as reported in Maroszek et al. [91] study. Extrusion through a confined nozzle imposes shear and confinement on the fresh mix, which acts as a form of process induced compaction [14]. This promotes particle rearrangement, reduces entrapped air and macro-voids, and increases packing density compared to cast specimens that are typically placed with limited shear history and may retain air pockets depending on moulding and compaction effort [44]. In addition, the layer-wise deposition process influences moisture redistribution and drying pathways, potentially affecting suction development and interparticle bonding during hardening, which may further contribute to strength differences between printed and cast specimens [13,14]. Interestingly, this behaviour differs from that observed in 3D-printed concrete, where casted specimens typically exhibit higher compressive strength than printed specimens [92]. These findings suggest that the 3D printing process itself may contribute to strength enhancement in soil-based materials, an area that requires further investigation. In any case, these data lack some important information, including suction levels or water content at the time of testing, which, in turn, strongly influence their mechanical strength.

Beyond compressive strength, tensile and flexural strength are also critical in determining the resistance of printed structures to bending and cracking. Alqenaee et al. [25] found that printed cob cylinders exhibited higher tensile strength compared to casted specimens, with notable differences in failure modes. Bhusal et al. [28] reported flexural strength values of 4.15 MPa, highlighting the ability of printed soil structures to withstand bending stresses. Further, the inclusion of graphene nanoplatelets (GNPs) was reported to improve mechanical properties, with lower concentrations (0.1 wt%) enhancing compression and flexural strength, while higher concentrations (0.2 to 0.3%) negatively impacted the performance due to agglomeration effects [93]. These findings indicate that strength enhancement strategies require a proper balance between reinforcement efficiency and potential material drawbacks.

Moreover, the role of microstructural arrangement of soil and swelling behaviour of soil particles has been identified to play a significant part in governing the mechanical performance of soil structures. Rückrich et al. [23] emphasised that both intraparticle and interparticle swelling contribute to soil cohesiveness and overall strength, making these important considerations in optimising soil mixtures for printing applications. Additionally, microstructural characterisation studies have revealed that the orientation of soil particles during printing differs from that in conventional compacted soil structures, leading to variations in drying as well as mechanical performance [75].

The drying process is the primary mechanism responsible for strength development in 3D-printed soil, but this process is inherently slow, limiting its applicability in commercial-scale construction. To accelerate strength gain, Perrot et al. [39] investigated the addition of 3% alginate (fast setting binder) to soil mixes and found that printed walls of 1m could sustain their weight within just 0.1 h, compared to more than 24 h required for pure soil mixes. However, while alginate facilitated early strength gain, the final compressive strength of printed samples remained around 1.2 MPa (1.21 for printed material with alginate and 1.22 without alginate), which aligns with conventional cob earth construction [39].

Apart from the composition and binders, the density of the infill material and the structural pattern used for the printed elements also important role in determining the mechanical performance. Research utilising Fibre Bragg Grating (FBG) sensors to measure the strain distributions demonstrated that increasing infill density from 40% to 100% resulted in higher lateral strain, providing insights into the deformation behaviour of 3D-printed soil under different loading conditions [76]. Additionally, the infill pattern influences crack propagation resistance, thereby improving the overall durability and structural integrity of printed structures [59].

The mechanical properties of 3D-printed soil are governed by the combined effects of material composition, mix design, additives, and printing parameters. While some studies report higher compressive strength for printed specimens than for cast specimens, the available data remain limited, and further studies are required to establish a comprehensive database for comparison. Moreover, the use of binders, fibre reinforcement, and microstructural optimisation presents promising pathways for improving load-bearing capacity, durability, and performance in soil-based 3D printing. Future studies should focus on developing standardised testing protocols to ensure consistency across studies and facilitate the broader adoption of 3D-printed soil in sustainable construction.

4.5. Environmental impact and sustainability

The sustainability of soil-based 3D printing has received attention as an alternative to conventional construction methods, particularly when comparing concrete 3D printing, which has a high environmental impact due to its dependence on cement. Several studies emphasise that printing with soil can reduce material processing, limit construction waste, and enable the use of locally available resources. By using excavated soil, this method transforms an environmental challenge (soil waste management) into a viable construction resource, minimising the need for mass-produced materials and significantly cutting down on transportation emissions [27,70].

One of the key environmental benefits of soil-based 3D printing is the reduction in cement consumption, which directly translates to lower carbon emissions. Cement production is a major contributor to global CO_2 emissions, and by significantly reducing its use, soil-based 3D printing results in a lower embodied carbon intensity [70]. Life cycle assessment indicates that structures built using 3D-printed soil can achieve 20% less carbon emissions compared to traditional materials when assessed on a material mass basis [16, 27]. This reduction is primarily caused by lower processing energy, reduced material waste and the use of locally sourced or recycled soil [16]. In the referenced study, the LCA was conducted using a cradle to grave system boundary, accounting for raw material extraction, transportation, material processing, manufacturing, use phase and end of life phase with carbon emissions reported per tonne of material produced. Compared to conventional material with an average carbon footprint of approximately 500 kg CO_2 eq/ton, the 3D printed soil-based material exhibited an embodied carbon of around 400 kg CO_2 eq/ton [16]. However, as no 3D-printed earth structures have yet been inhabited, decommissioned, or subjected to end-of-life processing to date, the assessment was limited to material quantities, and a comprehensive LCA including operational energy consumption and end-of-life phase has not been conducted [16]. Although the reported reduction is dependent on the system boundaries, functional units and material assumptions, compared to concrete-based 3D printing, soil-based printing has a lower global warming potential and overall lower environmental impact [94].

The use of natural fibres, such as hemp and straw, not only improves the mechanical properties of the printed structures but also contributes to ductility and thermal resistivity, making buildings more energy-efficient and durable [95]. Additionally, incorporating recycled construction waste into 3D-printed soil mixes supports circular construction approach, reducing material waste while maintaining or even improving compressive strength [16,42,43,61]. Life cycle assessment studies report that the use of recycled concrete aggregates (RCA) can reduce aggregate-related greenhouse gas emissions by up to 22–65% compared to natural aggregates, depending on processing methods and transport distances [96–98]. In construction-scale applications, the partial replacement of natural aggregates with RCA has been shown to reduce embodied carbon by approximately 70–100 kg CO_2 per m^3 of material [97,99]. Although the direct application of RCA in soil-based 3D printing remains limited, several studies have demonstrated the successful integration of recycled mineral fractions and construction waste into printable soil and geopolymer-based systems without compromising printability or compressive strength.

Beyond material sustainability, energy consumption in soil 3D printing is relatively low compared to conventional construction methods. The process typically relies on low-embodied-energy materials, which require minimal processing, thereby reducing overall energy demand [70]. Studies also report that 3D printing enables optimal material usage, allowing for the creation of complex architectural geometries with minimal waste [70]. As a result, soil-based 3D printing aligns with construction approaches that emphasise resource efficiency through process control and fabrication strategy, rather than through post-processing or material intensive solutions.

Soil 3D printing offers a viable pathway towards more sustainable construction, offering a low-carbon, resource-efficient alternative to traditional building methods. By using local materials, reducing waste, minimising energy consumption, and integrating recycled components, this technology aligns with circular economy principles while addressing environmental challenges [27,70]. Continued research into material optimisation, alternative binders, and long-term performance will be critical to fully use the potential of soil-based 3D printing in the transition toward greener and more resilient construction practices [94].

5. Challenges and future direction

Despite the promising advancements in soil-based 3D printing, several challenges must be addressed to enable its widespread adoption in the construction industry. These challenges primarily revolve around material consistency, printability issues, shrinkage and cracking, mechanical performance, and limitations in field application. Addressing these challenges will require innovations in material science, process optimisation, and the development of standardised testing protocols. This section outlines the key challenges identified from the reviewed studies and discusses potential remedies to overcome these challenges. The future research should converge towards a unified testing framework for soil-based 3D printing comprising.

I. Set of reference fresh state tests (E.g., cone penetration test or vane shear test for yield stress analysis and a standardised buildability test).
II. Standardised specimen geometries and curing conditions for mechanical testing.
III. Reporting protocols relating to mix composition, rheological parameters and printing settings.

Such a framework would enable reproducible results across soil types, printers and laboratories and would provide a practical foundation for translating laboratory results to field-scale applications.

5.1. *Material consistency and variability*

Achieving consistent material properties remains a significant challenge in soil-based 3D printing. The natural variability of soil composition results in differences in printability, strength, and durability, making it difficult to standardise material performance across different projects [62]. Bhusal et al. [28] found that the presence of 15% nontronite clay in soil mixtures led to excessive drying shrinkage and cracking, affecting the structural integrity of printed components. The unstable structure of clay contributed to volume changes under wetting and drying cycles, complicating its use in construction applications [28]. Similarly, El Aabbas et al. [17] highlighted the variability in local clay properties, which significantly impacts the uniformity of mechanical properties in printed elements.

To address these material inconsistencies, a two-stage characterisation protocol can be adopted for soils intended for printing. The first stage can focus on soil classification (Particle size distribution, soil composition, consistency limits), while the second stage targets printability screening linked to these data with emphasis on fresh state parameters such as static yield stress, flowability and buildability. Establishing a small set of reference soils (E.g. High plastic clay rich, moderate plasticity and sand rich low plasticity) and reporting mix performance relative to the reference values would help improve the comparability of studies and support printer-to-printer transferability [22,30,100]. It is also important to develop standardised testing methods to evaluate flowability, pumpability, and extrudability of soil mixes. These assessments will help ensure quality control across different batches. Analysed studies, as discussed, have explored various stabilisers for improving strength, although the effectiveness is limited, indicating the need for further research into more effective stabilising agents.

5.2. *Water content management*

The water content of the soil-based mix, as discussed in Section 4.3.1, is a critical factor influencing flowability and extrudability. Reported printable water contents in extrusion-based soil 3D printing typically fall within relatively narrow ranges and vary depending on soil mineralogy and stabilisation strategy. For instance, fibre-reinforced sand–clay mixtures have been successfully printed at water contents of approximately 23–25%, whereas clay-rich or biopolymer-stabilised mixes often require higher water contents, with values reported up to 40–45% to achieve continuous extrusion [22,37,39].Even minor variations in water content can significantly impact

(a)

(b)

Fig. 12. Freshly printed and cured 3DP beam using cob mixture (a) Before modifying mixture for shrinkage and (b) after modifying mixture for shrinkage [25].

printability (leading to nozzle clogging [101], deformation of layers [22] or collapse of the printed structure [100]), requiring precise monitoring and adjustments during the preparation process [62]. Water content governs the balance between yield stress, viscosity, and thixotropic rebuild of the soil-based mix, which directly controls extrusion continuity and post-deposition stability. At low water contents, high particle friction and limited lubrication increase yield stress and pumping resistance, resulting in discontinuous extrusion, tearing of filaments, and nozzle clogging. Conversely, excessive water content reduces yield stress and structural build-up after extrusion, causing the deposited filament to behave in a more fluid-like manner, leading to layer spreading, loss of geometric fidelity, and, in extreme cases, collapse under self-weight. These failure modes are consistent with reported inverse relationships between water content and yield stress for printable soil mixes [22,26,44].

The sensitivity of these failure mechanisms is strongly dependent on soil type. Clay-rich soils generally exhibit higher cohesion and thixotropic structural rebuild, allowing them to tolerate slightly higher water contents while maintaining buildability, although increased clay activity may increase shrinkage and cracking during drying [23,26]. In contrast, sand-rich or low-plasticity soils possess limited cohesion and rely primarily on particle friction and suction for stability, resulting in a much lower range of workable moisture content and a higher susceptibility to slumping or layer deformation when water content increases [23,25]. These differences highlight the importance of defining soil-specific printability windows rather than adopting a single target water content across different soil types.

To mitigate water-related printability issues during printing, Rückrich et al. [62] conducted preliminary tests to determine optimal water content, ensuring material stability during printing and drying. Although these tests provide guidance on how to adjust water levels to improve workability without compromising structural integrity, maintaining consistent water content while printing remains challenging due to external factors such as evaporation, temperature and ambient humidity, especially during extended printing durations.

Potential solutions to address these challenges include defining a printability window by relating water content directly to key rheological parameters such as yield stress, viscosity and thixotropy, which allows for accurate control of extrusion and layer stability. Future studies should report a soil specific workable moisture window rather than a single target water content by relating water content with at least one measurable printing parameter (static yield stress, penetration resistance, etc.) and a flow parameter (extrusion continuity). Additionally, sealed material chambers and humidity-controlled printing environments can help reduce moisture loss and improve consistency between batches. Future research should focus on combining these strategies into standardised protocols that integrate material preparation, environmental conditioning and sensor-enabled 3D printing systems, ensuring stable water content management and reliable print quality in soil-based printing.

5.3. Shrinkage and cracking

One of the most pressing concerns in soil-based 3D printing is shrinkage and cracking during the drying process (desiccation cracking). Soil containing a higher amount of clay is known for its tendency to undergo excessive shrinkage [102]. Excessive shrinkage can weaken the bond between printed layers, reducing the overall strength of the structure [62]. This effect was observed in a 3D-printed beam, as shown in Fig. 12(a) [25]. Moreover, Bhusal et al. [28] observed that high nontronite clay content in soil mixtures resulted in severe shrinkage and cracking, limiting its applicability in real-world construction.

Several strategies have been implemented to reduce shrinkage and cracking in the available studies. Rückrich et al. [62] successfully incorporated cellulose microfibers, which enhanced cohesiveness and flexibility in the material, thereby minimising crack formation. Nevertheless, Rückrich et al. [62] noted that while cellulose microfibers can help mitigate cracking, balancing the mixture composition remained a significant challenge. Bhusal et al. [28] found that the addition of natural fibres (1.5% by weight, wheat straw fibres) reduced shrinkage to 2.6%, and maximum crack widths decreased from 0.95 mm to 0.46 mm. Alqaneeh et al. [25] addressed shrinkage effects by modifying the tool path design, allowing for uniform shrinkage rather than isolated filament shrinkage. They also adjusted the water and sand content while increasing lime content, significantly reducing shrinkage (Fig. 12(b)). Additionally, slower drying rates have been found to mitigate shrinkage; Zavaleta et al. [14] reported that chitosan-stabilised samples retained more moisture, losing only 10% of their water content in the first five days, compared to 22% for control samples.

The type and proportion of clay significantly influence the overall shrinkage behaviour of soil, thereby affecting the susceptibility of earth-based structures to shrinkage. Ferretti et al. [74] investigated shrinkage strains in both 3D-printed and traditionally cast blocks, concluding that the shrinkage behaviour was comparable in both cases. This finding indicates that the 3D printing process does not adversely impact the shrinkage performance of earth-based constructions [25].

Nevertheless, to improve shrinkage performance in soil-based 3D printed elements, a combined approach that integrates additive incorporation with process control is imperative. The incorporation of fibres has been shown to enhance flexibility and reduce crack propagation [62], while biopolymer additives improve water retention and regulate drying rates [14], thereby minimising desiccation cracking. In addition to this, adjusting soil composition through controlled clay to sand ratios and the use of stabilisers such as lime can further mitigate shrinkage by reducing plasticity and increasing dimensional stability [25,28]. Process-oriented solutions, such as optimising tool path design and controlling the drying environmental conditions, can further help reduce shrinkage by promoting uniform stress distribution and gradual moisture loss [25]. Future research should focus on real-time monitoring of deformation and drying during printing, which can allow for dynamic adjustment of printing parameters to optimise shrinkage performance.

5.4. *Field testing limitations*

Conducting field tests for soil-based 3D printing presents logistical challenges. Evaluating properties such as green strength and structural stability requires immediate testing before printing, which necessitates the development of reliable and quick assessment methods [62]. Rückrich et al. [62] has proposed a field-oriented methodology and onsite tests for excavated soil mixes, but their transferability across different types of printers, nozzle geometries, and local soil has not been tested at scale. Moreover, the in-situ tests (such as rotational rheometer [22] and vane shear tests [39]) proposed are resource-intensive and difficult to replicate for very plastic mixes. In contrast, cylinder build-up tests with collapse observation and digital image correlation have also been used to quantify deformation and failure mechanisms during printing [22,28]. However, the material and time consumption of the cylinder build-up test limits its routine use on construction sites. Developing in-situ testing protocols such as a short buildability test (a defined number of layers printed at constant settings with deformation limits) and portable measurement techniques (rapid static yield stress measurement equipment), could streamline the assessment of soil mixes in real-time. This would allow for adjustments before printing begins, ensuring the structural viability of the printed elements.

5.5. *Variability in additives and binders*

Natural fibres and stabilisers are often incorporated in soil mixes to enhances the mechanical properties of 3D-printed soil. However, their effects can be unpredictable. Rückrich et al. [62] demonstrated that incorporating cellulose microfibres increased variability in the measured properties, complicating mix optimisation. At low to moderate dosages, plant based or cellulose fibres can enhance cohesion and mitigate shrinkage cracking. In contrast, higher fibre fractions have been linked to practical printing issues, including nozzle blockage, weak interlayer fusion, and dimensional inaccuracies [95].

Stabiliser composition also shows similar sensitivity. Bhusal et al. [28] found that lime and pozzolana did not provide the expected improvements in strength, shrinkage control, or printability, indicating the need for more effective stabilising agents. Alternative approaches using chitosan or starch modified soil mixes have been reported to improve moisture retention, water durability, and early strength; however, sensitivity to polymer characteristics and ambient curing has limited the transfer of results between sites [44,103]. Further work therefore needs to concentrate on identifying and optimising additive combinations that enhance printability and mechanical performance without introducing excessive variability. The development of hybrid binders, such as bio-based stabilisers, could provide a more consistent alternative to conventional stabilisers. Additionally, to reduce inconsistent results, future studies should report additive characteristics that control behaviour rather than only dosage. For fibres, this includes fibre length, aspect ratio and preconditioning state. For polymers, concentration, molecular characteristics, mixing sequence and rest time before printing can be included.

5.6. *Flowability issues during printing*

Maintaining proper layer dimensions is a common challenge in soil 3D printing. Bhusal et al. [28] found that the intended 20 mm layer width was not achieved, with over-extrusion occurring, particularly in fibre-reinforced mixes. Similarly, Zavaleta et al. [14] faced extrudability challenges, where improper mix composition led to inconsistent material flow during printing. Bhusal et al. [28] experimented with water content adjustments to improve flowability, finding that increasing water content enhanced material workability while reducing over-extrusion. Zavaleta et al. [14] optimised mix composition to ensure smooth extrusion without blockages, thereby improving print quality.

In addition to adjusting mix proportions, improving flowability during printing requires strict control of fresh state rheology. Previous studies related to 3D concrete printing recommend defining a printability window using static yield stress, plastic viscosity, and thixotropy, and then aligning nozzle height, travel speed, and extrusion rate to stay within the limits during deposition [104,105]. Further research is required to establish such printability windows in the context of soil-based 3D printing, which can help reduce flowability issues during printing.

5.7. *Mechanical strength limitations*

Raw soil as a construction material has inherently low mechanical strength (Fig. 11), making it brittle and less durable under mechanical loads. This limits its application in structural engineering, where higher load-bearing capacity is required. To improve mechanical strength, some of the studies have incorporated additives such as chitosan, natural fibres, cement etc.

Table 5, Fig. 10). For instance, Zavaleta et al. [14] incorporated chitosan and sisal fibres, which enhanced compressive strength and overall structural integrity.

Therefore, a potential solution to overcome mechanical strength limitations is to adopt a combined reinforcement and stabilisation technique. The utilisation of natural or synthetic fibres not only improves tensile strength resistance but also helps bridge cracks, enhancing ductility and post-failure performance [28]. Stabilisers such as chitosan and alginate regulate drying, increase cohesion and contribute to higher compressive strength compared to untreated mixes [14,106]. In addition to material level optimisation, strengthening interlayer bonding through controlled printing intervals and nozzle path design can also improve structural integrity by minimising weak planes between layers. Future research should explore alternative natural binders, reinforcements and design optimisation tools to further improve the strength and durability of soil-based 3D-printed structures. To support field-scale adoption, future studies should couple compressive strength with interface-controlled performance indicators, such as interlayer bond strength or anisotropy ratios (printed parallel vs perpendicular to layers), reported under clearly stated curing and suction or moisture conditions at testing [17,57,76]. This would help distinguish whether strength improvements originate from material stabilisation, printing-induced fabric, or improved interface quality.

5.8. *Common failure modes and need for durability research*

Several failure modes have been observed in soil 3D printing, including surface tearing from heterogeneous mixtures [27], cracking due to differential drying [43], and buckling under self-weight during printing [27]. Interlayer debonding has also been identified as a common failure, particularly when the time duration between layers while printing is large or when the nozzle standoff distance and extrusion flow rate are not well matched. Additional process-induced defects include voids from over or under extrusion and pump failures [27]. The drying process has also been shown to control several early-age failures: rapid moisture loss produces differential shrinkage and surface tearing, whereas slower drying reduces cracking but can prolong weak green strength. In printed soil, structural build-up has been reported as highly sensitive to ambient temperature and humidity, reinforcing the need for controlled curing or protective measures during field printing [78].

Despite these observations, systematic characterisation of failure mechanisms and evidence on long-term durability and weather resistance remains limited. Stabilisation strategies have been shown to play a key role in improving resistance to moisture-induced degradation. In particular, hydrated lime is widely used in earthen construction and soil-based 3D printing to reduce water absorption, limit swelling, and improve long-term durability by enhancing particle bonding and reducing moisture sensitivity [28]. Similarly, bio-based binders such as chitosan and starch have been reported to improve moisture retention, water durability, and early-age strength by promoting cohesive bonding and reducing susceptibility to rapid drying and erosion [44].

In addition to material composition, structural configuration and printing strategy also influence durability. The infill pattern has been shown to affect crack propagation resistance and stress redistribution, thereby improving the overall durability and structural integrity of printed elements [59]. Fibre reinforcement further contributes to durability by bridging microcracks, reducing shrinkage-induced cracking, and enhancing resistance to mechanical and environmental damage [74]. While these approaches demonstrate promising pathways for improving load-bearing capacity and durability, long-term performance under aggressive environmental conditions such as repeated wetting and drying cycles, rainfall exposure, and humidity fluctuations has not yet been systematically evaluated for soil-based 3D-printed structures. Most available evidence are from conventional earthen construction, highlighting the need for printed-specific durability studies that account for layer interfaces, anisotropy, and process-induced porosity.

6. Conclusion and recommendations

This review provides a comprehensive analysis of soil-based additive manufacturing in the construction domain. It outlines the core technologies employed in 3D printing with soil, highlighting the influence of various factors on printability, structural performance, and practical scalability. In this context, the review synthesises findings related to the rheological, mechanical, and environmental behaviour of 3D-printed soil mixtures, detailing how variations in soil composition, water content, extrusion systems, and stabilisers affect buildability, strength, and dimensional stability. Additionally, the review presents a focus on sustainability by evaluating the environmental benefits of soil printing, especially in reducing cement usage, enabling material circularity, and promoting low-carbon construction.

Furthermore, this review identifies the technological challenges, inconsistencies in testing practices, and knowledge gaps that currently hinder the transition of 3D soil printing from experimental settings to full-scale construction. The following conclusions can be drawn from this systematic review.

- Design of 3D printable mixes plays a critical role in printability and shrinkage performance. The optimal balance between clay, sand, water content, and additives is highly dependent on soil type. Natural fibres, biopolymers like alginate and starch gel, and lime-based stabilisers show promising improvement in cohesion, reducing shrinkage, and enhancing early strength.
- Shrinkage and cracking remain key concerns, especially in high clay-content compositions. Additives such as fibres and chitosan, along with modified printing paths and slower drying rates, have demonstrated effectiveness in reducing crack formation and dimensional instability.

- Mechanical strength of 3D-printed soil varies significantly. While compressive strength values of up to 6.17 MPa have been achieved, many mixes remain brittle. In particular, some 3D-printed specimens slightly outperformed the cast ones, possibly due to the fabric produced by the printing.
- Sustainability is a key strength of soil 3D printing. Life cycle assessments indicate that soil-based structures can reduce emissions by 20% compared to traditional materials. The use of excavated soil, the incorporation of recycled materials, and the use of natural binders support circular economy goals in construction.
- Current research is dominated by architectural perspectives, with limited integration of soil mechanics principles such as plasticity index, suction, or porosity characterisation. This knowledge gap restricts the development of robust predictive models for performance assessment under real-world conditions.

However, there remains a considerable gap between laboratory research and practical implementation. Most studies lack in-situ validation, and field-specific parameters such as weather resistance, thermal performance, and real-time monitoring are not well understood. Future research should focus on establishing standardised testing protocols for both fresh and hardened soil mixes, while incorporating geotechnical principles such as consistency limits, hydro-mechanical behaviour, and soil classification frameworks into mix design and characterisation. Attention should also be directed towards improving the durability of printed structures by examining their resistance to thermal cycles, freeze–thaw conditions, and biological degradation. Further advancements in this domain depend on interdisciplinary collaboration between geotechnical engineers, materials scientists, and architects, enabling the integration of structural efficiency with architectural performance. Ultimately, advancing soil-based additive manufacturing requires a strategic combination of material innovation, process standardisation, and field-oriented research. By addressing these limitations, 3D-printed soil can become a viable, low-carbon, and regionally adaptable alternative to conventional construction, aligning with the global movement toward more sustainable and resilient built environments.

CRediT authorship contribution statement

Fathima Nifla: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation. **Pathmanathan Rajeev:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Funding acquisition, Data curation, Conceptualization. **Satheeskumar Navaratnam:** Writing – review & editing, Validation, Data curation. **Alessio Ferrari:** Writing – review & editing, Validation, Data curation. **Marco Rosone:** Writing – review & editing, Validation, Data curation, Conceptualization. **Marco Starvaggi:** Writing – original draft, Formal analysis, Data curation. **Jay Sanjayan:** Writing – review & editing, Validation, Supervision, Resources, Funding acquisition, Conceptualization. **Emad Gad:** Writing – review & editing, Validation, Supervision, Resources, Funding acquisition, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A

Table A1
Search strategy and screening workflow

Step	Phase	Actions and criteria	Outcome (n studies)
1	Identification	In this process, predefined search criteria including two groups of keywords were used. Group 1 focused on capturing papers related to 3D printing, while Group 2 aimed to narrow the results to those addressing 3D printing of soil in construction applications. An asterisk (*) was used as a wildcard to accommodate variations in spelling, such as 3D print(ing) and 3D print(ed). Peer-reviewed articles from scientific journals that included at least one keyword from each group were selected. The search terms used in each group were as follows: Group 1: "Additive manufacturing", "Additive construction", "3D print*", "3D soil printing", "Construction 4.0" Group 2: "Soil", "Earth Construction", "Geotechnical Engineering", "Sustainable Earth Based construction", "Earth Constr*", "Earth", "Clay" The search was conducted in title, abstract, and keywords	10,105
2	Screening	Limiters were used in this phase to further filter the database on the most specific area as engineering, and the language as English	4460
3	Eligibility	The 4460 studies that were selected in Step 2 were further screened to exclude irrelevant articles and journals that are out of scope of this review. The titles of the studies that were more relevant to the assessment of 3D printing/Additive manufacturing in the soil-based context were sorted.	250
4	Inclusion	By analysing the abstracts and conclusion sections, 81 articles were included for detailed content analysis to review the development of additive manufacturing/3D printing of soil and clay-based materials. Among these articles, 49 experimental studies were selected for full text screening that focused on three critical aspects of additive	49

(*continued on next page*)

Table A1 (*continued*)

Step	Phase	Actions and criteria	Outcome (n studies)
		manufacturing namely, physical properties, fresh properties and hardened properties of 3D printed soil/clay specimen, as shown in Table A2. From the selected studies, 36 studies were finally selected for critical review that focused on extrusion-based 3D printing of soil/clay, which studied at least 2 aspects considered.	

Table A2
Content analysis of studies used for full-text screening.

#	Authors	Year	Material	Printing method	Parameters								Ref
					Physical property	Fresh properties					Hardened properties		
						Rheology properties			Extrudability	Buildability	Mechanical properties	Thermal properties	
						Yield stress	Viscosity	Thixotropy					
1	Aabbas et al.	2024	Clay	Screw extrusion	✓	×	×	×	-	×	✓	✓	[17]
2	Perrot et al.	2018	Raw earth and commercial alginate	Extrusion printing (6 axis industrial robot)	×	✓	×	×	-	×	✓	×	[39]
3	Bhusal et al.	2023	Well graded sand stabilised with lime, fibre and pozzolona	Extrusion printing (Gantry printer)	✓	✓	✓	✓	✓	✓	✓	×	[28]
4	Asaf et al.	2023	Clay sand mix	Extrusion printing (Robotic arm)	✓	✓	✓	×	-	✓	✓	×	[22]
5	Wu et al.	2024	Cob mix (soil reinforced with fibre/straw)	Extrusion printing (Robotic arm)	×	✓	×	×	✓	✓	✓	×	[107]
6	Curth et al.	2024	well graded soil/sandy clay loam stabilised with wheat straw	Extrusion printing (Robot arm)	✓	×	×	×	-	×	✓	×	[27]
7	Ferretti et al.	2022	Silty Clayey soil stabilised with lime and rice husk	Extrusion printing (Wasp Printer)	✓	×	×	×	-	-	✓	×	[59]
8	Zavaleta et al.	2024	Raw soil stabilised with chitosan and fibre	Extrusion printing (Gantry printer)	✓	✓	×	×	✓	✓	✓	×	[14]
9	Rückrich et al.	2024	Clay sand mix	Extrusion printing (Wasp Printer)	✓	×	×	×	-	✓	✓	×	[23]
10	Giudice et al.	2024	Quarts sand	Binder jetting	×	-	-	-	-	-	✓	×	[20]
11	Carcassi et al.	2024	Clay rich soil stabilised with fibre	Extrusion printing (Syringe)	✓	×	×	×	✓	-	✓	✓	[95]
12	Rückrich et al.	2023	coarse sand and kaolinite clay mix stabilised with fibres	Extrusion printing (Wasp Printer)	×	×	×	×	✓	✓	×	×	[62]
13	Wang et al.	2023	Homogenic sandstone or dolomitic marble.	Extrusion printing (robotic arm)	✓	×	×	×	×	×	✓	×	[54]
14	Tian et al.	2023	quartz sand powder	Binder jetting	×	-	-	-	-	-	✓	×	[51]
15	Mohsen et al.	2023	Clay enhanced with Graphene Nanoplates (GNPs) (Burnt)	Extrusion printing	✓	×	×	×	×	×	✓	×	[93]
16	Ma et al.	2023	Polylactic acid (PLA)	Fused deposition modelling	✓	×	×	×	-	-	×	×	[77]
17	Ji et al.	2023	Soil reinforced with flax fiber	Extrusion printing (Gantry printer)	×	✓	×	×	✓	✓	×	×	[26]
18	Faleschini et al.	2023	Soil stabilised with lime, marble waste, fly ash, rice husk and reinforced with natural fibres	Extrusion printing (Crane printer)	✓	×	×	×	✓	×	✓	×	[71]
19	Ferrari et al.	2022	Commercial clayey soil	Extrusion printing (Wasp printer)	✓	×	×	×	×	×	×	×	[108]

(continued on next page)

Table A2 (*continued*)

#	Authors	Year	Material	Printing method	Parameters								Ref
					Physical property	Fresh properties					Hardened properties		
						Rheology properties			Extrudability	Buildability	Mechanical properties	Thermal properties	
						Yield stress	Viscosity	Thixotropy					
20	Daher et al.	2023	Sandy silt soil mixed with cement and superplasticizer	Extrusion printing	✓	✓	×	×	✓	✓	✓	×	[70]
21	Bower et al.	2023	Commercial polymer clay (pvc combined with binder)	Extrusion printing (Vibration assisted printing)	✓	×	×	×	×	×	✓	×	[109]
22	Silva et al.	2022	Soil stabilised with potato starch gel and sisal fibers	Extrusion printing (Colibri)/ Gantry printer	✓	✓	×	×	✓	✓	✓	×	[44]
23	Ordoñez et al.	2022	Kaolin clay mixed with electric arc furnace dust (EAFD)	Extrusion printing (Direct ink writing)	✓	×	×	×	✓	×	✓	×	[110]
24	Mele et al.	2022	Clay enhanced by waste polyamide polymer	Fused deposition modelling	✓	×	×	×	✓	×	×	×	[111]
25	Ma et al.	2022	Polyactic acid (PLA)	Fused deposition modelling									[112]
26	Ilcan et al.	2022	construction and demolition waste (CDW) based geopolymer (clay, glass,concrete rubble) enhanced with alkaline activators	Extrusion printing	×	✓	✓	×	✓	✓	✓	×	[42]
27	Demiral et al.	2022	CDW stabilised and enhanced with alkaline activators (Sodium and calcium hydroxide)	Extrusion printing	-	×	×	×	×	×	✓	×	[61]
28	Barnes et al.	2022	Sand silt, clay mix incorporated with seeds	Extrusion printing	✓	×	×	×	✓	×	×	×	[30]
29	Alqaneeh et al.	2022	Clay sand mix stabilised with lime and fibre (Straw)	Extrusion printing (robotic arm)	✓	×	×	×	✓	✓	✓	×	[25]
30	Şahin et al.	2021	CDW stabilised enhanced with alkaline activators (Sodium and calcium hydroxide)	Extrusion printing	×	✓	×	×	✓	✓	✓	×	[43]
31	Pua et al.	2021	Kaolin and bentonite soil mix	Multi material extrusion printing	✓	×	×	×	×	×	×	×	[113]
32	Gomaa et al.	2021	Cob mix (soil reinforced with fibre (straw)	Extrusion printing (robotic arm)	×	×	×	×	×	×	✓	×	[24]
33	Gomaa et al.	2021	Cob mix (soil reinforced with fibre (straw)	extrusion printing (6 axis industrial robot)	×	×	×	×	✓	✓	×	×	[40]
34	Biggerstaff et al.	2021	Biopolymer-bound soil composite (BSC)	Extrusion printingˆ	×	✓	✓	×	×	×	×	×	[114]
35	Tang et al.	2020	Kaolin and barite clay powder	Extrusion printing (Direct ink writing)	✓	×	×	×	×	×	×	×	[115]
36	Kontovourkis and Tryfonos	2020	Clay sand mix stabilised using salt and sodium hexametaphosphate (clay deflocculant) and fibre (Straw)	Extrusion printing	-	×	×	×	✓	×	×	×	[41]
37	Chan et al.	2020	Clay paste	Extrusion printing (Direct ink writing)	✓	✓	✓	×	✓	×	×	×	[21]
38	Gomaa et al.	2019	Cob mix (soil reinforced with fibre (straw)	extrusion printing (6 axis	×	×	×	×	×	×	×	✓	[55]

(*continued on next page*)

Table A2 (*continued*)

#	Authors	Year	Material	Printing method	Parameters								Ref
					Physical property	Fresh properties					Hardened properties		
						Rheology properties			Extrudability	Buildability	Mechanical properties	Thermal properties	
						Yield stress	Viscosity	Thixotropy					
				industrial robot)									
39	He et al.	2018	Clay powder	Ink jet printing	✓	-	-	-	-	-	×	×	[52]
40	Zavaleta et al.	2025	Raw soil stabilised with ordinary Portland cement, rice husk	Extrusion printing (Industrial robotic arm)	✓	✓	×	✓	✓	✓	✓	×	[13]
41	Sangiorgio et al.	2025	Polyactic acid (PLA)	polymer extrusion	✓	×	×	×	×	×	✓	×	[116]
42	Akhrif et al.	2025	Clay powder	Extrusion printing	✓	✓	✓	×	✓	✓	✓	×	[46]
43	de Campos et al.	2025	Kaolin and bentonite powder	Extrusion printing	✓	✓	×	×	×	×	✓	×	[117]
44	Rückrich et al.	2025	Cob mix (soil reinforced with fibre)	Extrusion printing (Wasp Printer)	×	×	×	×	×	×	×	✓	[118]
45	El-Mahdy et al.	2025	Red earthenware clay	Extrusion printing (robotic arm)	✓	×	×	×	×	✓	×	×	[119]
46	Yousaf et al.	2025	Local soil stabilised with recycled coconut fibre and nanoclay	Extrusion printing (Wasp Printer)	✓	✓	✓	×	✓	✓	✓	×	[45]
47	Oulkhir et al.	2025	clayey soil stabilised with alginate	Extrusion printing	✓	✓	✓	×	✓	✓	×	×	[106]
48	El Mahdy et al.	2025	Pottery clay	Extrusion printing (Gantry printer)	✓	×	×	×	✓	✓	✓	×	[50]
49	Yousaf et al.	2025	Commercial earthen clay	Extrusion printing (Wasp Printer)	✓	×	✓	×	✓	✓	×	×	[101]

* ✓ indicates that the property was explicitly investigated and reported in the referenced study; × indicates that the property was not investigated in the study; and – indicates the property is not applicable to the referenced study.

Data availability

Data will be made available on request.

References

[1] J.W. Fassbinder, S. Hahn, M. Parsi, Geophysical prospecting on soils in mesopotamia: from mega-cities in the marches of southern Iraq to Assyrian sites in the Mountains of Kurdistan, World Archaeo-Geophysics (2024) 283.

[2] Y. Du, W. Chen, K. Cui, J. Zhang, Z. Chen, Q. Zhang, Damage assessment of earthen sites of the ming great wall in Qinghai province: a comparison between Support Vector Machine (SVM) and BP Neural Network, Journal on Computing and Cultural Heritage (JOCCH) 13 (2) (2020) 1–18.

[3] F. Parisi, N. Tarque, H. Varum, J. Vargas-Neumann, Adobe Constructions in the World: a First Overview, Structural Characterization and Seismic Retrofitting of Adobe Constructions: Experimental and Numerical Developments, 2021, pp. 1–14.

[4] C. Costa, Â. Cerqueira, F. Rocha, A. Velosa, The sustainability of adobe construction: past to future, Int. J. Architect. Herit. 13 (2019) 639–647.

[5] G. Giada, R. Caponetto, F. Nocera, Hygrothermal properties of raw earth materials: a literature review, Sustainability 11 (19) (2019) 5342.

[6] M. Hussain, I. Lamrous, A. Provost, N. Leblanc, H. Zmamou, D. Levacher, A. Kane, Recovery and restructuring of fine and coarse soil fractions as earthen construction materials, Sustainability 16 (20) (2024) 8952.

[7] G. Scialpi, D. Perrotti, The use of urban biowaste and excavated soil in the construction sector: a literature review, Waste Manag. Res. 40 (3) (2022) 262–273.

[8] Q.-B. Bui, J.-C. Morel, S. Hans, P. Walker, Effect of moisture content on the mechanical characteristics of rammed earth, Constr. Build. Mater. 54 (2014) 163–169.

[9] T. Sesay, Y. Xie, Y. Chen, J. Xue, Bio-based stabilization of natural soil for rammed Earth construction: a review on mechanical and water durability performance, Polymers 17 (9) (2025).

[10] E. Worrell, L. Price, N. Martin, C. Hendriks, L.O. Meida, Carbon dioxide emissions from the global cement industry, Annu. Rev. Energy Environ. 26 (1) (2001) 303–329.

[11] T.D. Ngo, A. Kashani, G. Imbalzano, K.T. Nguyen, D. Hui, Additive manufacturing (3D printing): a review of materials, methods, applications and challenges, Compos. B Eng. 143 (2018) 172–196.

[12] Y.W.D. Tay, B. Panda, S.C. Paul, N.A. Noor Mohamed, M.J. Tan, K.F. Leong, 3D printing trends in building and construction industry: a review, Virtual Phys. Prototyp. 12 (3) (2017) 261–276.

[13] D. Zavaleta, A. Quispe, O. Rojas, G. Silva, S. Kim, J. Nakamatsu, G. Ruiz, M.A. Pando, R. Aguilar, 3D-Printing of a basic housing unit prototype using earthen-based matrices stabilized with rice husk fibers, J. Build. Eng. (2025) 112111.

[14] D. Zavaleta, R. Ñañez, G. Silva, G. Ruiz, M.A. Pando, R. Aguilar, J. Nakamatsu, S. Kim, Additive construction using enhanced earthen-based composites: improvement of the mechanical strength and water durability using chitosan and agave fibers, Constr. Build. Mater. 411 (2024) 134159.

[15] Y. Maierdan, S.J. Armistead, R.A. Mikofsky, Q. Huang, L. Ben-Alon, W.V. Srubar, S. Kawashima, Rheology and 3D printing of alginate bio-stabilized earth concrete, Cement Concr. Res. 175 (2024).

[16] Z. Lai, Y. Chen, From wreckage to resource: advanced 3D printing materials from construction waste for energy infrastructure, J. Renew. Sustain. Energy 16 (3) (2024).

[17] M. El Aabbas, M. Mahdaoui, M. Ahachad, B. Mazian, I. Aalil, M. Ouardouz, Advancing sustainable construction: terracotta component development through extrusion-based 3d printing with local clay, Constr. Build. Mater. 442 (2024) 137549.

[18] M. Moretti, A. Chiusoli, L. Naldoni, F. De Fabritiis, M. Visonà, Earthen 3d printed constructions towards a new high-efficient way of building, in: L. Luvidi, F. Fratini, S. Rescic, J. Zhang (Eds.), Past and Present of the Earthen Architectures in China and Italy, 2021, pp. 147–155.

[19] A. Curth, B. Darweesh, L. Arja, R. Rael, Advances in 3D printed earth architecture: on-site prototyping with local materials, BE-AM| Building Environment Additive Manufacturing (2020) 105–110.

[20] L. Del Giudice, A. Katsamakas, B. Liu, V. Sarhosis, M.F. Vassiliou, Physical modelling of unreinforced masonry walls using a sand-based 3D printer, Eng. Struct. 305 (2024).

[21] S.S. Chan, R.M. Pennings, L. Edwards, G.V. Franks, 3D printing of clay for decorative architectural applications: effect of solids volume fraction on rheology and printability, Addit. Manuf. 35 (2020) 101335.

[22] O. Asaf, A. Bentur, P. Larianovsky, A. Sprecher, From soil to printed structures: a systematic approach to designing clay-based materials for 3D printing in construction and architecture, Constr. Build. Mater. 408 (2023) 133783.

[23] S. Rückrich, G. Agranati, Y.J. Grobman, Evaluating clay characteristics for printable geo-materials: a case study of clay–sand mixes, Buildings 14 (6) (2024) 1576.

[24] M. Gomaa, J. Vaculik, V. Soebarto, M. Griffith, W. Jabi, Feasibility of 3DP cob walls under compression loads in low-rise construction, Constr. Build. Mater. 301 (2021) 124079.

[25] A. Alqenaee, A. Memari, Experimental study of 3D printable cob mixtures, Constr. Build. Mater. 324 (2022) 126574.

[26] Y. Ji, P. Poullain, N. Leklou, The selection and design of earthen materials for 3D printing, Constr. Build. Mater. 404 (2023) 133114.

[27] A. Curth, N. Pearl, A. Castro-Salazar, C. Mueller, L. Sass, 3D printing earth: local, circular material processing, fabrication methods, and Life Cycle Assessment, Constr. Build. Mater. 421 (2024) 135714.

[28] S. Bhusal, R. Sedghi, M. Hojati, Evaluating the printability and rheological and mechanical properties of 3D-Printed earthen mixes for carbon-neutral buildings, Sustainability 15 (21) (2023) 15617.

[29] V. Gentile, J.D. Vargas Velasquez, S. Fantucci, G. Autretto, R. Gabrieli, P.K. Gianchandani, M. Armandi, F. Baino, 3D-printed clay components with high surface area for passive indoor moisture buffering, J. Build. Eng. 91 (2024) 109631.

[30] S. Barnes, L. Kirssin, E. Needham, E. Baharlou, D. Carr, J. Ma, 3D printing of ecologically active soil structures, Addit. Manuf. 52 (2022) 102670.

[31] I. Corazza, TECLA Technology and Clay 3D Printed House / Mario Cucinella Architects, 27 Apr 2021. ArchDaily. Accessed 26 May 2026. <https://www.archdaily.com/960714/tecla-technology-and-clay-3d-printed-house-mario-cucinella-architects> ISSN 0719-8884.

[32] I. Baan, 3D Printed Earth Forest Campus in Collserola Natural Park (Barcelona) WASP, Delta WASP, 2024.

[33] Y.K. Abdallah, A.T. Estévez, 3D-printed biodigital clay bricks, Biomimetics 6 (4) (2021) 59.

[34] A. Wolf, P.L. Rosendahl, U. Knaack, Additive manufacturing of clay and ceramic building components, Autom. ConStruct. 133 (2022) 103956.

[35] K. Aghaee, L. Li, A. Roshan, P. Namakiaraghi, Additive manufacturing evolution in construction: from individual terrestrial to collective, aerial, and extraterrestrial applications, J. Build. Eng. (2024) 110389.

[36] M. Abedi, M.B. Waris, M.K. Al-Alawi, K.S. Al-Jabri, A.H. Al-Saidy, From local earth to modern structures: a critical review of 3D printed cement composites for sustainable and efficient construction, J. Build. Eng. 100 (2025) 111638.

[37] M. Gomaa, W. Jabi, V. Soebarto, Y.M. Xie, Digital manufacturing for earth construction: a critical review, J. Clean. Prod. 338 (2022) 130630.

[38] Scopus, Abstract and Citation Database.

[39] A. Perrot, D. Rangeard, E. Courteille, 3D printing of earth-based materials: processing aspects, Constr. Build. Mater. 172 (2018) 670–676.

[40] M. Gomaa, W. Jabi, A.V. Reyes, V. Soebarto, 3D printing system for earth-based construction: case study of cob, Autom. ConStruct. 124 (2021) 103577.

[41] O. Kontovourkis, G. Tryfonos, Robotic 3D clay printing of prefabricated non-conventional wall components based on a parametric-integrated design, Autom. ConStruct. 110 (2020) 103005.

[42] H. Ilcan, O. Sahin, A. Kul, G. Yildirim, M. Sahmaran, Rheological properties and compressive strength of construction and demolition waste-based geopolymer mortars for 3D-Printing, Constr. Build. Mater. 328 (2022) 127114.

[43] O. Şahin, H. İlcan, A.T. Ateşli, A. Kul, G. Yıldırım, M. Şahmaran, Construction and demolition waste-based geopolymers suited for use in 3-dimensional additive manufacturing, Cement Concr. Compos. 121 (2021) 104088.

[44] G. Silva, R. Ñañez, D. Zavaleta, V. Burgos, S. Kim, G. Ruiz, M.A. Pando, R. Aguilar, J. Nakamatsu, Eco-friendly additive construction: analysis of the printability of earthen-based matrices stabilized with potato starch gel and sisal fibers, Constr. Build. Mater. 347 (2022) 128556.

[45] A. Yousaf, S.A. Khan, M. Koç, Material, process, and design optimization of local earthen soil reinforced with natural fiber waste and nanoclay for 3DP of functional structures, J. Build. Eng. 111 (2025) 113502.

[46] I. Akhrif, F.Z. Oulkhir, M. El Jai, N. Rihani, N.C. Igwe, S.E. Baalal, Earth-based materials 3D printing, extrudability and buildability numerical investigations, Progr. Addit. Manuf. 10 (9) (2025) 6873–6905.

[47] M. Starvaggi, M. Rosone, A. Ferrari, Creating controlled-double-structured Soils Through 3D Printing TC 105 International Symposium 23/09/2024 - 27/09/2024 Grenoble, France, IOP Conference Series: Earth and Environmental Science; 1480, Institute of Physics, 2025.

[48] M. Starvaggi, M. Rosone, P. Rajeev, A. Ferrari, Fabric evolution of a double-structured 3D-printed clayey soil upon drying. E3S Web of Conferences, EDP Sciences, 2025 03030.

[49] P. Shakor, S. Nejadi, G. Paul, S. Malek, Review of emerging additive manufacturing technologies in 3D printing of cementitious materials in the construction industry, Frontiers in Built Environment 4 (2019) 85.

[50] D. El-Mahdy, H. Sameh, M. Fekry, Structural stability of 3D-printed earthen catenary domes: experimental and analytical insights, Structures 81 (2025) 110273.

[51] Y. Tian, F. Wu, L. He, H. Tian, M. Huang, W. Chen, Investigation of 3D printing sand core technology on the mechanical behaviors of soft–hard interbedded rock masses, J. Mater. Civ. Eng. 35 (12) (2023) 04023440.

[52] Z. He, T. Shanmugasundaram, G. Singh, Inkjet 3D printing of clay ceramics for water treatment, Progr. Addit. Manuf. 3 (2018) 215–219.

[53] A. Meurisse, A. Makaya, C. Willsch, M. Sperl, Solar 3D printing of lunar regolith, Acta Astronaut. 152 (2018) 800–810.

[54] Y. Wang, G. Ma, L. Wang, W. Zhang, H. Liu, Size effects in cavern model tests based on 3D printing, Tunn. Undergr. Space Technol. 137 (2023) 105135.

[55] M. Gomaa, J. Carfrae, S. Goodhew, W. Jabi, A. Veliz Reyes, Thermal performance exploration of 3D printed cob, Archit. Sci. Rev. 62 (3) (2019) 230–237.

[56] J.A. Arrieta-Escobar, D. Derrien, S. Ouvrard, E. Asadollahi-Yazdi, A. Hassan, V. Boly, A.-J. Tinet, M.-F. Dignac, 3D printing: an emerging opportunity for soil science, Geoderma 378 (2020) 114588.

[57] J.-B. Izard, A. Dubor, P.-E. Hervé, E. Cabay, D. Culla, M. Rodriguez, M. Barrado, Large-scale 3D printing with cable-driven parallel robots, Construction Robotics 1 (1) (2017) 69–76.

[58] WASP, Clay 3D Printer, in: D.W.C. [Photograph] (Ed.) n.d.

[59] E. Ferretti, M. Moretti, A. Chiusoli, L. Naldoni, F. De Fabritiis, M. Visonà, Mechanical properties of a 3D-Printed Wall segment made with an earthen mixture, Materials 15 (2) (2022) 438.

[60] K. Manikandan, X. Jiang, A.A. Singh, B. Li, H. Qin, Effects of nozzle geometries on 3D printing of clay constructs: quantifying contour deviation and mechanical properties, Procedia Manuf. 48 (2020) 678–683.
[61] N.C. Demiral, M.O. Ekinci, O. Sahin, H. Ilcan, A. Kul, G. Yildirim, M. Sahmaran, Mechanical anisotropy evaluation and bonding properties of 3D-printable construction and demolition waste-based geopolymer mortars, Cement Concr. Compos. 134 (2022) 104814.
[62] S. Rückrich, G. Agranati, Y.J. Grobman, Earth-based additive manufacturing: a field-oriented methodology for evaluating material printability, Archit. Sci. Rev. 66 (2) (2023) 133–143.
[63] J. Jauk, L. Gosch, H. Vašatko, M. Königsberger, J. Schlusche, M. Stavric, Filament-reinforced 3D printing of clay, Materials 16 (18) (2023) 6253.
[64] G. Bai, L. Wang, G. Ma, J. Sanjayan, M. Bai, 3D printing eco-friendly concrete containing under-utilised and waste solids as aggregates, Cement Concr. Compos. 120 (2021) 104037.
[65] A. Perrot, D. Rangeard, Y. Mélinge, Prediction of the ram extrusion force of cement-based materials, Appl. Rheol. 24 (5) (2014) 34–40.
[66] P. Martin, D. Wilson, P. Bonnett, Paste extrusion through non-axisymmetric geometries: insights gained by application of a liquid phase drainage criterion, Powder Technol. 168 (2) (2006) 64–73.
[67] A.S.f. Testing, Materials, Standard Practice for Use of Apparatus for the Determination of Length Change of Hardened Cement Paste, Mortar, and Concrete, vol. 490, ASTM C-, West Conshohocken, 2011.
[68] H.B. Seed, R.J. Woodward, R. Lundgren, Fundamental aspects of the atterberg limits, J. Soil Mech. Found Div. 90 (6) (1964) 75–106.
[69] B. Panda, S. Ruan, C. Unluer, M.J. Tan, Improving the 3D printability of high volume fly ash mixtures via the use of nano attapulgite clay, Compos. B Eng. 165 (2019) 75–83.
[70] J. Daher, J. Kleib, M. Benzerzour, N.-E. Abriak, G. Aouad, The development of soil-based 3D-Printable mixtures: a mix-design methodology and a case study, Buildings 13 (7) (2023) 1618.
[71] F. Faleschini, D. Trento, M. Masoomi, C. Pellegrino, M.A. Zanini, Sustainable mixes for 3D printing of earth-based constructions, Constr. Build. Mater. 398 (2023) 132496.
[72] S. Bhattacherjee, A.S. Basavaraj, A. Rahul, M. Santhanam, R. Gettu, B. Panda, E. Schlangen, Y. Chen, O. Copuroglu, G. Ma, Sustainable materials for 3D concrete printing, Cement Concr. Compos. 122 (2021) 104156.
[73] K.L. Bar-Sinai, T. Shaked, A. Sprecher, Robotic tools, native matter: workflow and methods for geomaterial reconstitution using additive manufacturing, Archit. Sci. Rev. 64 (6) (2021) 490–503.
[74] E. Ferretti, M. Moretti, A. Chiusoli, L. Naldoni, F. De Fabritiis, M. Visonà, Rice-husk shredding as a means of increasing the long-term mechanical properties of earthen mixtures for 3D printing, Materials 15 (3) (2022) 743.
[75] A. Ferrari, M. Rosone, S. La Rosa, G. Sapienza, Microstructural characterization of a 3D-printed soil, Soils and Rocks 45 (4) (2022) e2022005422.
[76] C. Hong, X. Wang, K. Han, D. Su, Z. Chen, Performance investigation of 3D printed clay soil using fiber bragg grating technology, Acta Geotech. 17 (2) (2022) 453–462.
[77] X. Ma, H. Lei, X. Kang, Examination of interface roughness and particle morphology on granular soil–structure shearing behavior using DEM and 3D printing, Eng. Struct. 290 (2023) 116365.
[78] M. Motamedi, R. Mesnil, A.-M. Tang, J.-M. Pereira, O. Baverel, Structural build-up of 3D printed earth by drying, Addit. Manuf. 95 (2024) 104492.
[79] N. Labonnote, A. Rønnquist, B. Manum, P. Rüther, Additive construction: state-of-the-art, challenges and opportunities, Autom. ConStruct. 72 (2016) 347–366.
[80] V. Mechtcherine, F.P. Bos, A. Perrot, W.L. Da Silva, V. Nerella, S. Fataei, R.J. Wolfs, M. Sonebi, N. Roussel, Extrusion-based additive manufacturing with cement-based materials–production steps, processes, and their underlying physics: a review, Cement Concr. Res. 132 (2020) 106037.
[81] C. Astm 230, Standard Specification for Flow Table for Use in Tests of Hydraulic Cement, ASTM International, West Conshohocken, PA, 2008.
[82] C. Pedrajas, V. Rahhal, R. Talero, Determination of characteristic rheological parameters in Portland cement pastes, Constr. Build. Mater. 51 (2014) 484–491.
[83] M. Saresma, D.J. White, D. Mohapatra, S. Mohammadi, W. Sołowski, L. Korkiala-Tanttu, J.J. Virtasalo, S. Gourvenec, Assessment of near-surface undrained shear strength of soft seabeds with free fall cone penetrometer testing in the northern Baltic Sea, Eng. Geol. 346 (2025) 107906.
[84] D. Astm, Standard Test Method for Laboratory Miniature Vane Shear Test for Saturated fine-grained Clayey Soil, American Society for Testing and Materials, West Conshohocken, PA, 2016.
[85] A.V. Benedito, C.A. Benedetty Torres, R.M.d.C. Silva, P.A. Krahl, D.C.T. Cardoso, F.d.A. Silva, C.H. Martins, Effects of niobium addition on the mechanical properties and corrosion resistance of microalloyed steels: a review, Buildings 14 (5) (2024) 1462.
[86] N. Roussel, A thixotropy model for fresh fluid concretes: theory, validation and applications, Cement Concr. Res. 36 (10) (2006) 1797–1806.
[87] T.T. Le, S.A. Austin, S. Lim, R.A. Buswell, A.G.F. Gibb, T. Thorpe, Mix design and fresh properties for high-performance printing concrete, Mater. Struct. 45 (8) (2012) 1221–1232.
[88] J. Oti, J. Kinuthia, Engineering properties of concrete made with brick dust waste, in: 9th International Concrete Conference, 2016, pp. 70–77.
[89] K. Roscoe, H. Poorooshasb, A theoretical and experimental study of strains in triaxial compression tests on normally consolidated clays, Geotechnique 13 (1) (1963) 12–38.
[90] V.A. Hernández-Hernández, D.R. Joya-Cárdenas, L.N. Equihua-Anguiano, J.C. Leal-Vaca, J.A. Peña, L. Pérez-Moreno, N. Saldaña-Robles, A. Saldaña-Robles, Experimental and numerical analysis of triaxial compression test for a clay soil, Chil. J. Agric. Res. 81 (3) (2021) 357–367.
[91] M. Maroszek, I. Hager, K. Mróz, M. Sitarz, M. Hebda, Anisotropy of mechanical properties of 3D-Printed Materials—Influence of application time of subsequent layers, Materials 18 (16) (2025) 3845.
[92] A.U. Rehman, J.-H. Kim, 3D concrete printing: a systematic review of rheology, mix designs, mechanical, microstructural, and durability characteristics, Materials 14 (14) (2021) 3800.
[93] M.O. Mohsen, M.M. Al-Diseet, M.O. Aburumman, R. Taha, A.A. Taqa, A. Senouci, K. Naji, 3D-Printed clay enhanced with graphene nanoplatelets for sustainable and green construction, Buildings 13 (9) (2023) 2321.
[94] H. Alhumayani, M. Gomaa, V. Soebarto, W. Jabi, Environmental assessment of large-scale 3D printing in construction: a comparative study between cob and concrete, J. Clean. Prod. 270 (2020) 122463.
[95] O.B. Carcassi, Y. Maierdan, T. Akemah, S. Kawashima, L. Ben-Alon, Maximizing fiber content in 3D-printed earth materials: printability, mechanical, thermal and environmental assessments, Constr. Build. Mater. 425 (2024).
[96] Z. Peng, W. Lu, C.J. Webster, Quantifying the embodied carbon saving potential of recycling construction and demolition waste in the Greater Bay Area, China: status quo and future scenarios, Sci. Total Environ. 792 (2021) 148427.
[97] M. Bravo, J. de Brito, J. Pontes, L. Evangelista, Mechanical performance of concrete made with aggregates from construction and demolition waste recycling plants, J. Clean. Prod. 99 (2015) 59–74.
[98] X. Huang, Y. Ouyang, D. Zhang, H. Yu, Greenhouse gas emission of recycled concrete production for pavement construction considering carbon uptake, Dev. Built Environ. 22 (2025) 100646.
[99] T. Nian, Y. Li, X. Jin, Z. Wang, M. Wang, Y. Wang, Toward carbon balance in life cycle: the carbon emission assessment for the recycled coarse aggregate concrete, Adv. Civ. Eng. 2025 (1) (2025) 9184976.
[100] N. Dal Ferro, F. Morari, From real soils to 3D-printed soils: reproduction of complex pore network at the real size in a silty-loam soil, Soil Sci. Soc. Am. J. 79 (4) (2015) 1008–1017.
[101] A. Yousaf, A. Al Rashid, M. Koç, Parameter tuning for sustainable 3D Printing(3DP) of clay structures, Journal of Engineering Research 13 (3) (2025) 1826–1842.
[102] T.L. Piani, D. Krabbenborg, J. Weerheijm, L. Koene, L.J. Sluijs, The mechanical performance of traditional adobe masonry components: an experimental-analytical characterization of soil bricks and mud mortar, J. green. building 13 (3) (2018) 17–44.
[103] D. Zavaleta, R. Ñañez, G. Silva, S. Kim, G. Ruiz, M.A. Pando, J. Nakamatsu, R. Aguilar, Evaluation of chitosan and potato starch as stabilizers to improve the mechanical and water durability properties of printable earth-based matrices reinforced with sisal fibers, Materials Science Forum, Trans Tech Publ (2023) 151–159.

[104] W. Si, M. Khan, C. McNally, A comprehensive review of rheological dynamics and process parameters in 3D concrete printing, J. Compos. Sci. 9 (6) (2025) 299.

[105] R. Jayathilakage, P. Rajeev, J. Sanjayan, Rheometry for concrete 3D printing: a review and an experimental comparison, Buildings 12 (8) (2022) 1190.

[106] F.Z. Oulkhir, I. Akhrif, M. El Jai, N. Rihani, Clay and alginate-based mixtures 3D printing: a numerical procedure for shape stability and buildability assessment, Progr. Addit. Manuf.10 (2025) 10999–11039.

[107] X. Wu, Q. Shi, J. Huo, Y. Zhao, L. Zhu, Y. Tao, Experimental study on buildability and mechanical properties of 3D printing cob, Constr. Build. Mater. 453 (2024) 139082.

[108] A. Dutto, M. Zanini, E. Jeoffroy, E. Tervoort, S.A. Mhatre, Z.B. Seibold, M. Bechthold, A.R. Studart, 3D printing of hierarchical porous ceramics for thermal insulation and evaporative cooling, Adv. Mater. Technol. 8 (4) (2023) 2201109.

[109] K. Bower, M. Örnek, T. Ansell, I.E. Gunduz, Microstructures and failure in 3D printed viscous materials, Addit. Manuf. 74 (2023) 103710.

[110] E. Ordoñez, S.N. Monteiro, H.A. Colorado, Valorization of a hazardous waste with 3D-printing: combination of kaolin clay and electric arc furnace dust from the steel making industry, Mater. Des. 217 (2022) 110617.

[111] M. Mele, M. Ricciarelli, G. Campana, 3D printing of clay paste enhanced by scrap polymer from powder bed processes, Rapid Prototyp. J. 28 (2) (2022) 285–296.

[112] X. Ma, H. Lei, X. Kang, Effects of particle morphology on the shear response of granular soils by discrete element method and 3D printing technology, Int. J. Numer. Anal. Methods GeoMech. 46 (11) (2022) 2191–2208.

[113] L.-M. Pua, J. Macedo, J.P. Villacreses, B. Caicedo, F. Yépez, A homogenization approach to estimate the shear modulus of spatially variable soil materials, Soil Dynam. Earthq. Eng. 151 (2021) 106970.

[114] A. Biggerstaff, G. Fuller, M. Lepech, D. Loftus, Determining the yield stress of a Biopolymer-bound soil composite for extrusion-based 3D printing applications, Constr. Build. Mater. 305 (2021) 124730.

[115] D. Tang, L. Hao, Y. Li, Z. Li, Effect of clay functionally graded materials on dual gradient direct ink writing behavior and microstructure of geological model, Rapid Prototyp. J. 26 (1) (2020) 39–48.

[116] V. Sangiorgio, P. Rossetti, A. Polidoro, E. Rossi, Sustainable raw-earth blocks achieved with 3D-printed formworks: parametric modeling, prototyping, and laboratory testing, Archit. Sci. Rev. 1-13.

[117] G. Pante Leme de Campos, P. Sinigaglia Lunelli, E. Guzi de Moraes, M. Tramontin Souza, A.P. Novaes de Oliveira, Optimization of clay-based ceramic mixtures with sugarcane bagasse fiber for 3D printing, Case Stud. Constr. Mater. 22 (2025) e04693.

[118] S. Rückrich, G. Austern, O. Denay, P. Seiwert, Y. Sterman, S. Selvan, E. Tarazi, A. Yezioro, Y.J. Grobman, 3D-printed earth-fiber envelopes: optimization of thermal performance and industrial applicability, J. Build. Eng. 109 (2025) 113006.

[119] D. El-Mahdy, S. Dara, M. AbdelRahim, Evaluating structure stability of self-supporting 3D printed earth-based cantilevers using robotic ARM, Architect. Eng. Des. Manag. 1-24.