

Applications and effectiveness of additive manufacturing in geotechnics – A systematic review

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Review Article

Keywords

Geotechnics
Additive manufacturing
3D printing
Porosity
Sample acquisition

Abstract

One of the greatest challenges of rock and soil studies is acquiring a sufficient number of samples with adequate characteristics. 3D printing, also known as additive manufacturing or rapid prototyping, is an emerging technique that allows researchers to obtain an unlimited number of samples with the desired geometries and properties. Recent studies also indicate that rapid prototyping is better than the traditional methods to create micromodels. 3D printing is a vast field, with many possible techniques and materials. To better understand the benefits, limitations and applications of the current technology, this article did a systematic review of the literature published in recent years. The search was limited to documents published in English between 2014 and 2024. The only inclusion criterion applied was that the study 3D printed soil or rock analogues. After applying this criterion, and removing duplicates or non-relevant results, a total of 66 documents remained for review. It was possible to observe some printers are already able to reach the nanoscale accuracy and create pores at the natural scale. However, their printing time is significantly longer than other printers, and the material used is not suitable for replicating mechanical properties. Even so, printers able to reproduce mechanical and chemical characteristics are not yet capable of reaching that accuracy. It was possible to conclude that the current technology has its applications and is capable of being a useful tool in geotechnics. Nevertheless, there has to be further improvement in the printing technology for it to reach its full potential.

1. Introduction

Additive manufacturing is a relatively new and rapidly evolving technology, and it has revolutionized many different fields. In civil engineering, structures are being built using 3D printed concrete and mortar. Abdalla et al. (2021) concluded that, in their context, the cost of a 3D-printed house was lower than that of one built with traditional methods. Ceccanti et al. (2010) obtained promising results when investigating the feasibility and profitability of using 3D printers to construct Moon outposts with lunar soil. Zhong & Zhang (2022) presented a literature review of 3D-printed geopolymers and concluded that issues such as drying shrinkage and long-term durability require further investigation.

Hasheminezhad et al. (2025) 3D-printed geosynthetics using recycled plastic and tested their performance in stabilizing an unpaved road. While their results were promising, the authors raised concerns about the durability and long-term behavior of the material. These limitations align with the findings of Maraveas et al. (2024), who concluded that the technique is not yet viable for large-scale applications.

In geoscience, Kong et al. (2021a) identified four major advantages of 3D printing.

The first advantage is the ability to recreate samples. Acquiring natural specimens is often challenging, which frequently leads to the avoidance of destructive tests. However, by combining rapid prototyping with digitizing techniques, it is possible to acquire a virtually unlimited number of samples. For example, Zhang & Li (2022) conducted Brazilian splitting test on 12 identical 3D-printed samples, subjected to different cycles of freezing and thawing. The authors observed a strong correlation between the cycles and the degradation of mechanical properties. The changes noted resemble those of high-porosity weak rocks.

The second is its ability to create physical replicas of digital models, enabling researchers to refine and validate their numerical simulations. Dimou et al. (2022) examined 3D-printed micromodels for single phase flow and concluded that rapid prototyping not only can be used to study CO₂ sequestration, enhanced oil recovery, and geothermal energy applications but is also more cost-effective than traditional micromodel methods.

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Submitted on July 29, 2024; Final Acceptance on June 26, 2025; Discussion open until May 31, 2026.

Editor: Renato P. Cunha 

<https://doi.org/10.28927/SR.2026.005924>



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Third is the production of specimens with desired shape, size, and material properties. Additive manufacturing allows researchers to isolate and vary individual properties, enabling better test control and result interpretation. By changing the grain size of the material used and the layer thickness, Wang et al. (2022) obtained samples with identical geometry but different mechanical properties. They observed that both parameters significantly influence physical properties, compressive strength, and failure behavior. A decrease in layer thickness results in a decrease in porosity but an increase in peak strength and density. Meanwhile, samples with the higher content of coarse grain showed lower porosity, higher peak strength, and higher density.

The fourth is its ability to create models with extremely complex pore networks. For example, Head & Vanorio (2016) studied the effect of rock microstructure on permeability. The authors simulated compaction and dissolution using a known power law relating permeability to porosity, determining the power law coefficient for each case. The authors suggest that, with further research, additive manufacturing could enhance the understanding of the physical meaning of this coefficient.

Gao et al. (2021) reviewed the applications of 3D printing in rock mechanics, while Arrieta-Escobar et al. (2020) focused on its use in soil science. Yu & Tian (2024) also conducted a review in the context of rock mechanics but limited their scope to sand-based 3D printing. Although these reviews provide valuable insights, there remains a lack of an up-to-date, comprehensive systematic review that explores the applications and limitations from a broader geotechnical perspective, as most reviews tend to focus on a specific field, material, or technology.

The main objective of this article is to determine the limits of current technology through a systematic review of the literature. A secondary objective is to identify the geotechnical areas where additive manufacturing is employed and assess the adequacy of the results.

2. The basics of 3D printing

There are many different technologies of rapid prototyping, with their advantages and limitations. In this article, they were classified into seven major categories per ASTM 52900 (ASTM, 2021): Binder Jetting (BJT), Direct Energy Deposition (DED), Material Extrusion (MEX), Material Jetting (MJM), Powder Bed Fusion (PBF), Sheet Lamination (SHL) and Vat Photopolymerization (VPP).

In BJT, a roller spreads a layer of powder. Followed by the jetting of a binder to bond the material. This process repeats layer by layer until forming the desired structure. Figure 1a illustrates a BJT printer. The printing process in PBF printers, presented in Figure 1b, is similar to BJT. The main difference is that, instead of using a binder, PBF fuses the powder with an energy source.

DED employs a heat source, such as a laser or electron beam, to fuse material (wire or powder) and deposit it in layers onto a substrate. SHL, on the other hand, prints using thin sheets of material that are cut to shape and stacked, being bonded with adhesive, a bonding agent, heat, or pressure. Illustrations of DED and SHL processes are shown in Figure 2a and Figure 2b, respectively.

MEX uses extrusion to deposit material at a specified location, as shown in Figure 3. This classification is often subdivided based on the material used. Printers that heat material to the fusion point during printing are typically called filament printers, while those that do not use heat are known as ceramic printers.

Figure 4a and Figure 4b illustrate the VPP and MJM processes, respectively. MJM uses a photopolymer as construction material. The polymer is selectively deposited at the desired position and when exposed to a light source, the curing process starts, and the structure is built. VPP also uses photosensitive material. However, unlike MJM, in VPP

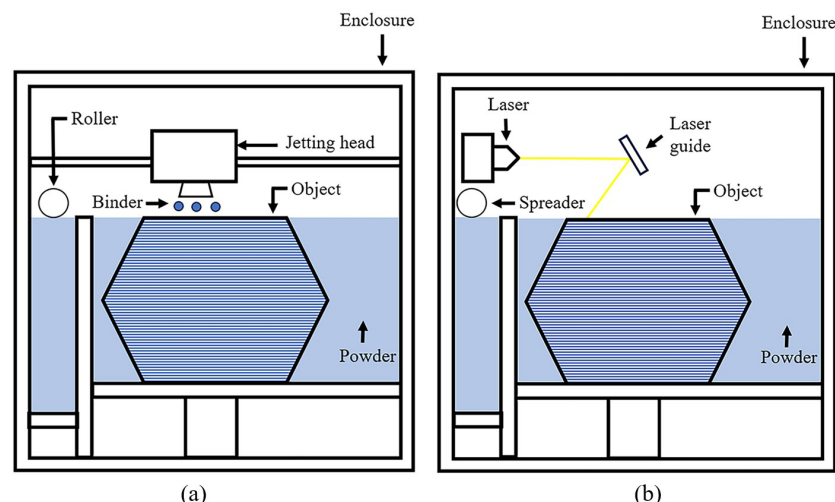


Figure 1. Printing process. (a) Binder Jetting. (b) Powder Bed Fusion.

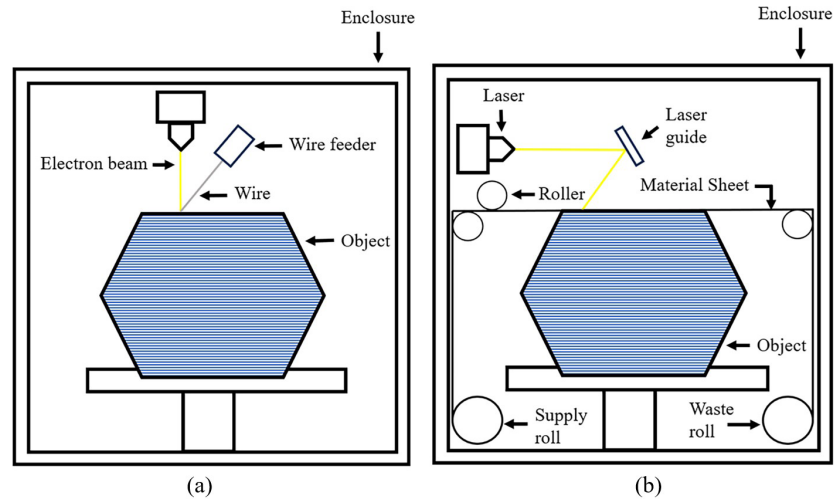


Figure 2. Printing process. (a) Direct energy deposition. (b) Sheet lamination.

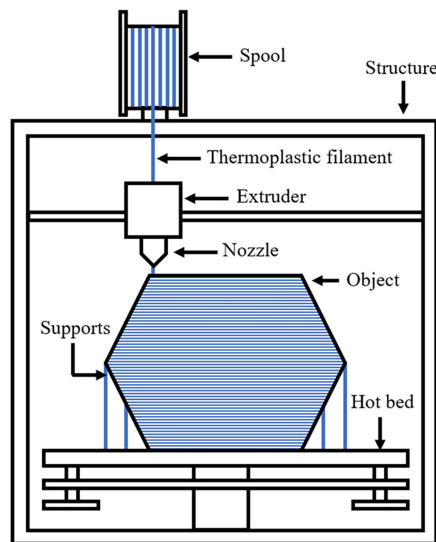


Figure 3. Printing process of a material extrusion printer.

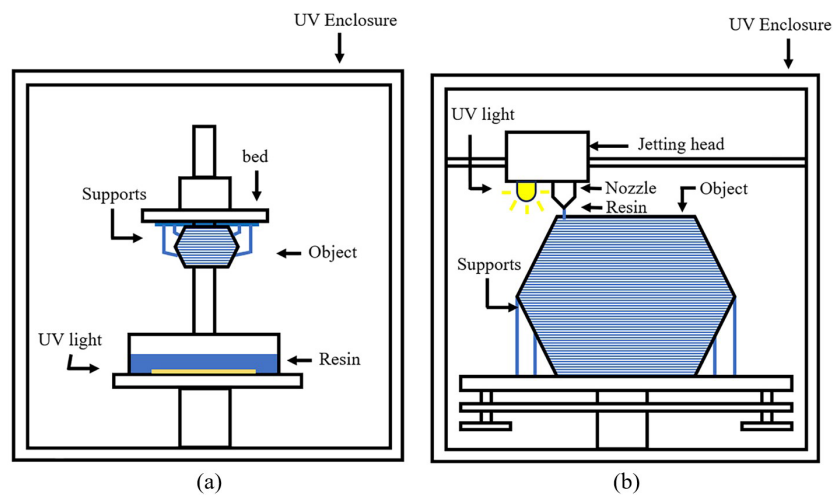


Figure 4. Printing process. (a) Vat photopolymerization. (b) Material jetting.

a vat is filled with the resin before the printing process. Afterwards, the resin is exposed selectively to a light source, which solidifies it.

Usually, the 3D printing process follows four steps: digital model design; model slicing; printing process; post-print processing. The most common ways of doing the first step are with scripts, computer aided design (CAD) or digital images (DI) of a natural sample. To slice the model a specific software is needed. During this step, it is important to properly adjust the printing parameters to achieve the desired result. The third and fourth steps are dependent on the printing technology and materials employed.

In Additive manufacturing it is possible to use many different materials depending on the technique employed. MEX can use ceramics materials, mortars, concrete or polymers. On the other hand, VPP, for instance, utilizes photosensitive resins, whereas BJT employs powder that may be polymeric, metallic, or ceramic, such as silica sand or natural soils.

The adequate choice of material is essential to print a model with the desired characteristics. Figure 5 shows a Berea sandstone core sample recreated by Almetwally & Jabbari (2021b) using different techniques and materials. Formlabs may be classified as a VPP printer, ProJet 660 as BJT, and the remaining printers as MEX.

The use of different printers complicates the isolation of materials effects. The original core exhibited a porosity of 20% and a permeability of 100 md. The cores closest to the original were the transparent resin and the sandstone ones, with 23% of porosity and 96 md of permeability for the former and 22% and 110 md for the latter. When comparing only the ones created with the Ultimaker printer, the authors obtained a difference of 13% in porosity and 20 md in permeability between printed cores. In both cases, the transparent CPE showed the highest values and ABS the lowest.

3. Methodology

The methodology used in this study is based on the guidelines proposed by Moher et al. (2009), named PRISMA

(Preferred Reporting Items for Systematic reviews and Meta-Analyses). The systematic review of the literature begins with the elaboration of the research question. Subsequently, the databases that will be used must be chosen and the search string(s) that address the research question(s) must be constructed.

By combining the result of the different databases and removing duplicates the initial sample is obtained. In the next step, selection criteria are defined, and the abstracts are reviewed. Finally, the documents selected in the previous process are read in full, at this stage, eventually, there may be both the elimination of articles, for reasons of access, language, or other reasons, as well as the addition of documents, based on the references or citations of the selected works.

In this study, the PICO methodology, introduced by Richardson et al. (1995), was chosen. In this methodology, P stands for the population being studied. I for the intervention being considered. C is the comparison, and O is the desired outcome.

It was considered that the population studied is the current 3D printing, the intervention performed is the printing of porous structures, the comparison is being made with natural soils or rocks, and the expected result is analogous pores/voids. Thus, the systematic review of the literature was based on the following question: “What is the effectiveness of current 3D printing technology in creating prototypes with porous structures similar to the natural soils and rocks?”.

In the present work, the research was limited to English and based on Scopus and the Web of Science (WoS) databases. As 3D printing technology is constantly evolving and the focus is on current techniques, documents with a publication date before 2014 were discarded. Conference articles were also excluded because the data they report tend to be limited.

In both databases, advanced search was used to search for the words chosen in the title, abstract, and keywords. Analyzing the research question, for the construction of the search string, three main elements were identified that should necessarily be present: 3D printing; Soil/Rock; Pore. Connecting these elements with the Boolean operators, the strings were elaborated as shown in Table 1.

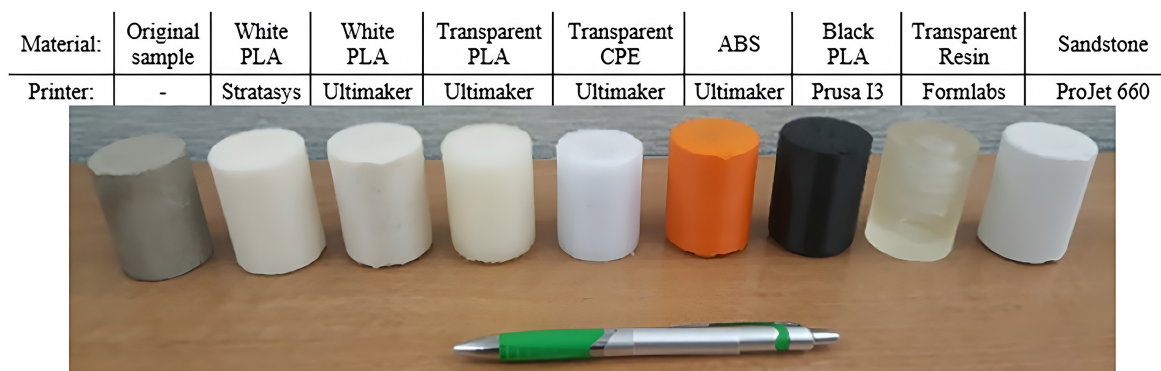
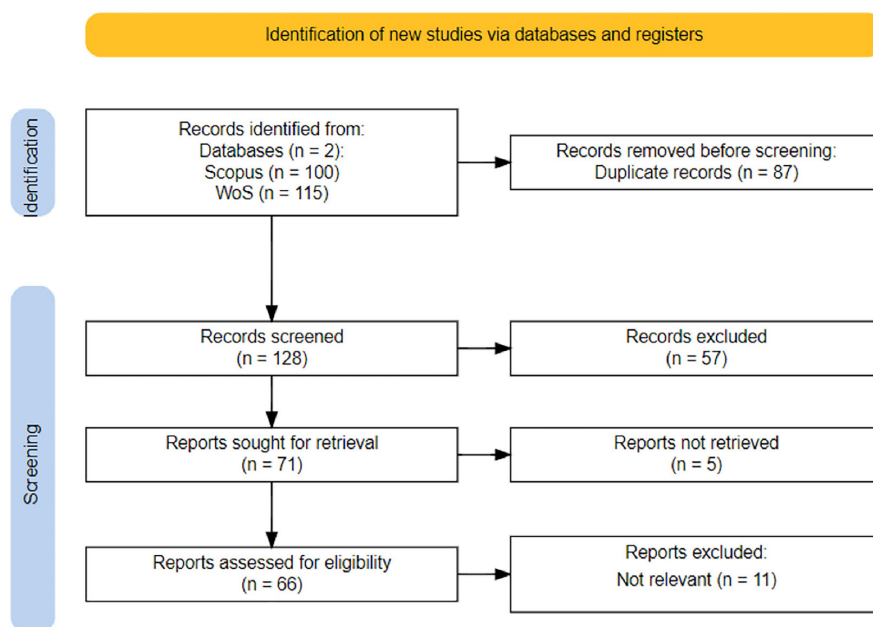


Figure 5. Original samples and models 3D printed with different materials. Adapted from Almetwally & Jabbari (2021b).

Table 1. Search string.

Base	String
Scopus	TITLE-ABS-KEY ((3d OR 3-d OR three) AND print*) OR TITLE-ABS-KEY (“additive manufacturing”) OR TITLE-ABS-KEY (“rapid prototyping”) AND TITLE-ABS-KEY (soil OR soils OR rock OR rocks) AND TITLE-ABS-KEY (pore OR porosity)
Web of Science	TS= (((3d OR 3-d OR three) AND print*) OR (“additive manufacturing”) OR (“rapid prototyping”)) AND (soil OR soils OR rock OR rocks) AND (pore OR porosity)

**Figure 6.** The PRISMA flowchart

The search was conducted in June 2023. In the Scopus database, 100 documents were obtained, while in the Web of Science 115. These results were exported to Mendeley, and the duplicates were removed. After this step, the total number of documents was 128. For the selection of the sample, a single elimination criterion was adopted: any article in which a three-dimensional specimen resembling rock or soil was printed was selected for full-text reading.

After the elimination criterion, the sample was reduced to 71 articles. Of those, 5 were not retrieved due to access reasons. During the full-text reading process, another 11 articles were excluded because they were judged as not relevant, resulting in a final sample of 55 documents. A flowchart describing the PRISMA process, made with the R package of Haddaway et al. (2022), is presented in Figure 6.

4. Bibliometric analysis

The bibliometric analysis was performed on the first sample, after the removal of the duplicates, with the aid of the bibliometrix, an R package presented by Aria & Cuccurullo (2017) and the software VOSviewer, by van Eck & Waltman (2010). This study verified the number of articles per year,

country production and published journals using bibliometrix and the keyword network using VOSviewer.

It is possible to observe in Figure 7 that there is a growth tendency in the number of articles per year. This indicates that there is interest from the international community in the subject and the research topic is promising.

Figure 8a shows the scientific production by country during the analyzed period. China and the United States leads the publications in 3D printing of soils and rocks. Regarding the source of those documents, as shown in Figure 8b, Transport in Porous Media and Petrophysics are the main publishers.

A keyword correlation analysis (Figure 9) was done to provide a preliminary understanding of the applications of the 3D printing in the geotechnical area. The minimum number of occurrences of a keyword was set to five and the words used on the search string were excluded. Of 1447 keywords of the sample, only 44 met the selected criteria. The number of occurrences of a keyword determines the size of the circles. The keyword that appeared the most was computerized tomography, followed by porous materials and pore structure.

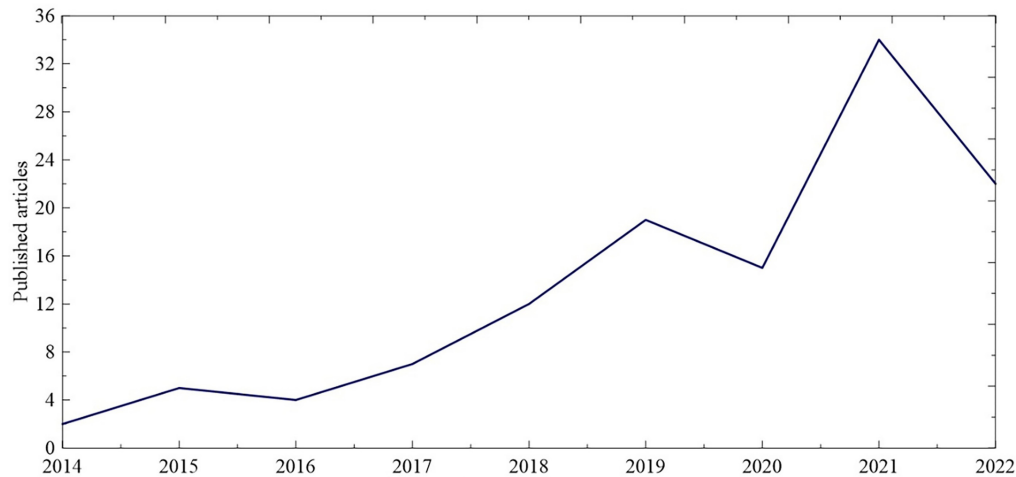


Figure 7. Annual production

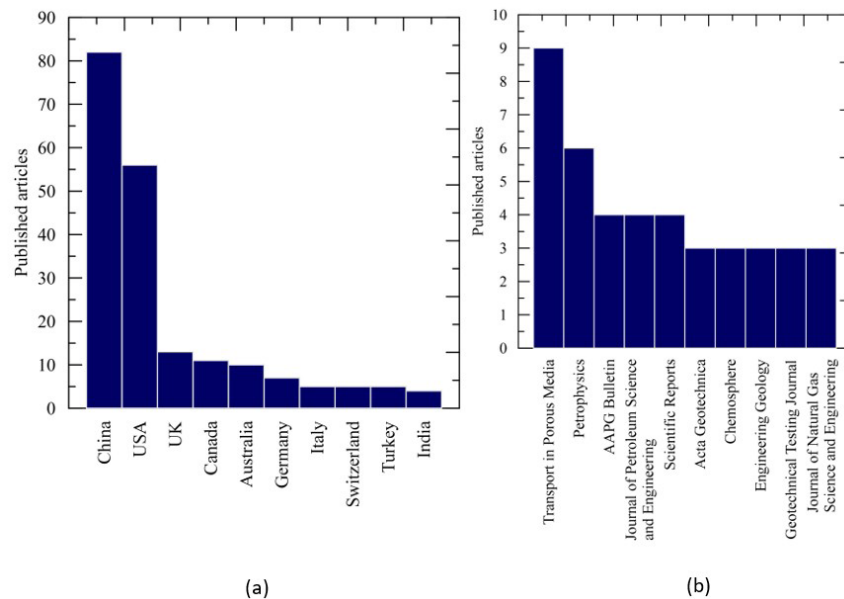


Figure 8. Number of published articles (a) by country and (b) by source.

5. Research progress

3D printing is a rapidly evolving technique. As new studies were published during the preparation of this paper, an additional search was conducted in November 2024 following the same methodology, resulting in 11 new documents, and bringing the total to 66. After selection, the sample was divided into rock and soil studies, with the most relevant data summarized in Table 2 (rocks) and Table 3 (soils).

A predominance of studies focused on rocks was observed (84.8%), while only 15.2% studied soils. One of the main reasons for that difference is the greater incentives, especially economic, for the studies of rocks. The oil industry

is an important contributor to these incentives, as evidenced by bibliometric analysis.

Some of the journals with the highest number of publications include *Transport in Porous Media*, *Petrophysics*, *AAPG Bulletin* and *Journal of Petroleum* of which three are directly linked to the oil industry. When observing the most common keyword network (Figure 9), it is possible to notice keywords associated with petroleum studies, such as “petrophysics”, “petroleum reservoirs” and “petroleum reservoirs engineering”.

The articles about soil, on the other hand, were more focused on studying the printed structure, with some also analyzing its effect on the transport properties. It was also

Table 2. Rock articles data.

Author	Digital Model	Tech. (a)	Material	Resolution (μm)		Porosity (%)		Study (b)
				xy	z	Original / Digital	Printed	
Hasiuk & Harding (2021)	-	MEX	- Limoges clay - ISU clay	-	100	0	39 36	I
Song et al. (2022)	Image based	VPP	- Resin	2	5	12.9	10	II
Almetwally & Jabbari (2021b)	Image based	VPP MEX BJT	- PLA - CPE - ABS - Resin - Sandstone	-	-	20	dec/28	I
Kong et al. (2021b)	Image based	BJT	- Gypsum powder	800	100	20	-	I
		VPP	- Silica sand - Resin	1000 140	280-500 25-100			
Song et al. (2020)	Image based	BJT	- Silica sand and furfuryl binder	-	200	24.6	38.2	III
		PBF	- Gypsum powder and furfuryl binder - Silica coated sand beads and phenolic binder		100		47.4	
Zhang & Li (2022)	-	BJT	- Silica sand and furan binder	-	260-380	-	24	III
Dimou et al. (2022)	Python code	VPP	- Resin	140	25-100	-	-	II
Hodder et al. (2021)	-	BJT	- Silica sand and furfuryl binder	-	-	-	35-55	I
Kong et al. (2018a)	CAD	BJT	- Gypsum powder	127 dpi	200	0	5.8	III
Almetwally & Jabbari (2021a)	Image based	BJT	- Gypsum powder and acrylic binder	-	3	20	22	II
Perras & Vogler (2019)	Image based	BJT	- Sand with furan and silicate binder - Ceramic beads with silicate binder	-	-	-	-	III
Head & Vanorio (2016)	Image based	VPP	- Resin	-	25	Varies	Varies	II
		MJM	- Polymer		16			
Wang et al. (2022)	-	BJT	- Silica sand (varied grain size) and furan resin as binder	300 dpi	200	-	40.6-49.4	III
Almetwally & Jabbari (2020)	Image based	BJT	- Gypsum powder	-	-	20	22	II
Santiago et al. (2022)	-	BJT	- Silica sand with furan binder	-	-	-	27-44	III II

a – Printer's technology (Tech.) was divided according to ASTM 52900 (ASTM, 2021). In some cases, the classification may not have been the same as the one used by the authors. b – Studies were classified according to their focus on the structural (I), transport (II) or mechanical (III) analysis. c – Resolution determined by the author.

Table 2. Continued...

Author	Digital Model	Tech. (a)	Material	Resolution (μm)		Porosity (%)		Study (b)
				xy	z	Original / Digital	Printed	
Gomez et al. (2019)	-	BJT	- Silica sand and furfuryl binder	-	-	-	35.7	III II
Ju et al. (2017)	Image based	MJM	- Polymer	600 dpi	16-30	-	-	III
Hodder et al. (2022)	-	BJT	- Silica sand powder and organic binder	-	350	-	40-51	III
Kong et al. (2019a)	Image based	BJT	- Silica sand and furfuryl binder	-	220	-	36-48	I
Kong et al. (2019b)	CAD	BJT	- PXL and different infiltrants	-	100	-	0.15-21.2	II
Elsayed et al. (2021)	Image based	-	- Resin	-	-	21.1 16.9-17.7	6.5 5.2-12.2	I
Kong et al. (2018b)	CAD	BJT	- Gypsum powder	127 dpi	200	-	32.7	I
Lesueur et al. (2021)	Image based	MEX	- PLA	-	-	-	-	III
Lesueur et al. (2023)	Image based	MEX	- PLA	-	-	-	-	III
Silva et al. (2023)	Algorithm Blender	BJT	- Ceramic powder	-	-	-	-	II
Ju et al. (2019)	Image based	MJM	- Polymer	100	100	-	-	III
Ju et al. (2018)	Image based	-	- Polymer	100	100	-	-	III
Ishutov et al. (2021)	Image based	VPP	- Resin	-	1	-	-	II
Ibrahim et al. (2021)	Image based	MJM	- Polymer	30	30	3.3-12.1	2.8-12.3	II
		VPP	- Resin	100	25			
Wu et al. (2022a)	Image based	MJM	- Polymer	-	14	-	-	III
Ju et al. (2022)	Image based	MJM	- Polymer	-	16	27	24-29	II
Hasiuk (2019)	CAD	PBF	- Aluminum powder	-	-	0	0.7-5.2	I
		BJT	- Stell powder				1.7-3.2	
			- Ceramic powder				0.9-1.5	
			- Silica sand				36-51	
			- Gypsum powder				mai/36	
Cruz-Maya et al. (2022)	Image based	MJM	- Polymer	-	16	-	14 (cemen-tation) 41-43	II
Jouini et al. (2021)	Image based	MJM	- Polymer	-	30	12.4-17.2	11.9-16.7	II
Hasiuk et al. (2018)	CAD	MJM	- Polymer	1600 dpi	16	0-1.3	0.2-1.9	I
Ishutov & Hasiuk (2017)	Image based	MJM	- Polymer	132 (c)	16	21.3	14	I
Li et al. (2021)	Image based	VPP	- Resin	0.5	-	20.3	17.8	II
Huang et al. (2016)	-	MEX	- ABS	-	-	0	6	III
						-	24	
Dande et al. (2021)	CAD	MEX	- ABS	-	160	0	6	III
							24	

a – Printer's technology (Tech.) was divided according to ASTM 52900 (ASTM, 2021). In some cases, the classification may not have been the same as the one used by the authors. b – Studies were classified according to their focus on the structural (I), transport (II) or mechanical (III) analysis. c – Resolution determined by the author.

Table 2. Continued...

Author	Digital Model	Tech. (a)	Material	Resolution (μm)		Porosity (%)		Study (b)
				xy	z	Original / Digital	Printed	
Ishutov (2019)	Image based	VPP	- Six distinct resins	-	50	12.7	0.5-12.4	II
Goral & Deo (2020)	Image based	VPP	- Resin	-	-	7.2	-	I
Ishutov et al. (2017)	Image based	BJT	- Calcined gypsum	150	100	13	28-37	II
Wollner et al. (2018)	Theoretic auxetic model	VPP	- Resin	-	-	-	53	III
Schafrik & Millar (2015)	Rosine-Rammler distribution/ PFC-3D/CAD	MEX	- ABS	-	254	46	-	II
Song et al. (2021)	Image based	MJM VPP	- Polymer - Resin	-	30	24.8	18.6	II
					60	24.8	20.2	
					20	25.6	14.3-18.4	
						31.8	20.6	
						10.0	7.4	
Ishutov et al. (2018)	Image based	VPP	- Resin	400 (c)	25	12.7	2-12 (pre-flushing) 8.4-12.8	I
Anjekar et al. (2020)	Image based	MEX	- HIPS	-	250	26	25-33	I
Wu et al. (2022b)	CAD	-	-	-	-	-	aug/36	III
Shao et al. (2023)	CAD	BJT	- Plaster-based powder	400 dpi	100	0	17.7-20.2	III
Zhang et al. (2023)	CAD	BJT	- Quartz sand and furan binder	-	26	-	-	III
Zhao et al. (2023)	-	BJT	- Silica sand and furan binder	-	300	9-32.2	35.4	III
Shao et al. (2024)	-	BJT	- Gypsum powder	-	100	-	Varies	III
Yu et al. (2024)	-	BJT	- Quartz sand and furan binder	-	-	-	6.2-49.5	III
Zhao et al. (2024)	Image based	BJT	- Gypsum powder and organic binder	-	100	25.4	22.3-27.8	III
		VPP			-			II
Oskolkov et al. (2024)	Image based	MEX	- PLA	5	2	14	12.8-13.5	II
Cruz-Maya et al. (2023)	Particle packing/ Image based	MJM	- Resin	-	16	28-41	26-40	II

a – Printer's technology (Tech.) was divided according to ASTM 52900 (ASTM, 2021). In some cases, the classification may not have been the same as the one used by the authors. b – Studies were classified according to their focus on the structural (I), transport (II) or mechanical (III) analysis. c – Resolution determined by the author.

observed that the soil function of food production plays an important part in the development of the field.

Bedell et al. (2021), for example, designed an open source tool chain to generate porous soil structures based on mathematical models. One of their goals was to simulate root systems on the model. Although they achieved this goal, the grain size was limited to a range between coarse sand and fine gravel.

Lamandé et al. (2021) studied the void structure of regularly tilled topsoil and undisturbed subsoil aiming to recreate them using additive manufacturing. The authors compared the original, artificial (created with other techniques) and printed cores, analyzing parameters, such as Darcian and apparent air permeability and oxygen diffusion. They concluded that the printed cores were good proxies

for specimens with a predominance of large continuous macropores.

Tang et al. (2018) and Matsumura et al. (2023) were the only studies, in the final sample focusing on the mechanical properties. By using wax-based barite slurry, Tang et al. (2018) tried to 3D print a landslide model. They were able to obtain a wide range of compressive strengths and replicate the structures of weak slip zones, concluding that the technique has a great potential of achieving control of material properties such as stress and seepage field in 3D models.

The first information extracted for Table 2 and Table 3 was the method to design the digital models, classified as image-based, CAD-designed, or created with other techniques (mainly scripts). As shown in Figure 10, most studies used digitized natural samples, while the other two methods were less common and nearly equally used.

CAD software is a quick and practical tool for designing simple digital models, but it becomes less suitable for replicating the complex structure of soils and rocks. Kong et al. (2019b) and Dande et al. (2021), for instance, used CAD to design solid cores with different printing techniques.

Kong et al. (2019b) used a BJT printer to produce porous cores by binding powder materials, a method that naturally results in inherent porosity. They analyzed structural properties such as porosity and permeability, varying infiltrants and coating conditions. The results showed that infiltrants mainly affected nanopores, while coatings had minimal impact on structure. Dande et al. (2021) printed a solid cube and a second model with a mesh of inclusions using MEX. Due to voids between layers, MEX-printed models also have inherent porosity. In their case, the solid model showed 6% porosity.

Besides complex models, numerical design is also preferred when significant model modifications are expected. Dimou et al. (2022) tested the viability of 3D printed micromodels, using a Python-based program to stochastically generate diverse structures with consistent statistical pore-space heterogeneity. In other cases, 3D printing technology is used only to validate numerical models. Wollner et al. (2018) proposed a theoretical auxetic structure based on the pore-space configuration of rocks and used 3D printing to create a physical model for Poisson's ratio testing.

The printing technique was the second information analyzed. BJT, VPP, MJM, and MEX, in that order, were the most used ones. PBF appeared in only 5% of the studies and no use of the other techniques were found. Figure 11 contains the number of articles by techniques.

Kong et al. (2021b) used BJT and VPP printers to replicate natural rocks and compared the two techniques. BJT allows high-speed, low-cost printing and supports a wider range of materials, enabling geomechanical testing with rock-like replicas. However, it has lower precision, requires complex postprocessing, and often produces occluded, powder-filled pores. They highlighted that VPP's superior resolution and capacity to produce complex structures make

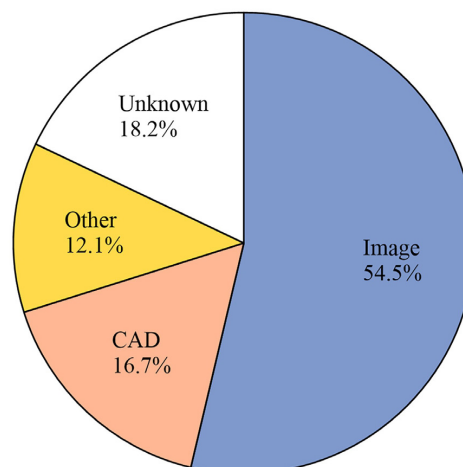


Figure 10. Design method

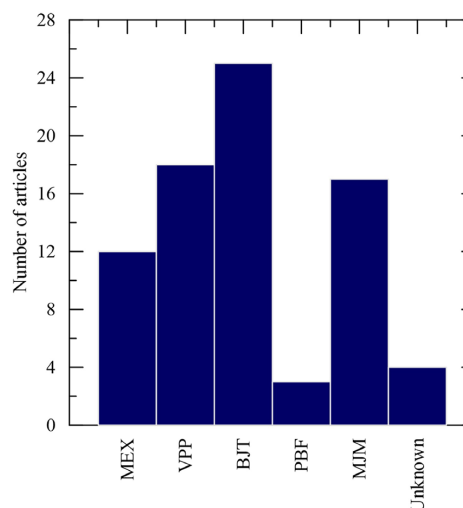


Figure 11. Printing technique employed

it suitable for single-phase flow studies. However, its limited material options hinder its use in multiphase flow modeling and stress-related tests.

MJM and VPP share many similarities both relying on exposing photosensitive material to light for solidification. While both methods have similar advantages and disadvantages compared to other 3D printing techniques, MJM's main benefit over VPP is its ability to use multiple materials simultaneously, allowing for more heterogeneous samples and simplifying support removal.

The material used is another important factor, as it affects the characteristics of the printed model. One of the key factors for BJT's popularity stems from its ability to use sandy powders. According to Song et al. (2020), polymers used in other techniques exhibit large plastic deformation and undesired surface properties, making them unsuitable for reproducing mechanical behavior. However, these

properties may not be relevant for all studies, and in some cases, materials offering higher accuracy may be more appropriate. Therefore, selecting the right material and printing techniques is essential.

Hasiuk (2019) used BJT and PBF to print solid cylinders of two different sizes. The inherent porosity also occurs with PBF. The study focused on the bulk properties of specimens printed with different powders. The author observed that the material significantly affects the porosity, and the size of the proxy is also capable of affecting the structure. Cores made with aluminum and ceramic powder had lowest porosity, 0.73% and 0.91% respectively, and were the only ones created with PBF. Of the proxy made with BJT, steel showed the lowest porosity (1.71%), while gypsum and silica produced much higher porosity values, 33.33% and 41.00%, respectively.

Perras & Vogler (2019) explored the compressive and tensile behavior of 3D printed cores and compared them with natural sandstones. They used sand grains with furan and silicate binders and ceramic beads with silicate binder from two different companies, totaling four different materials. The sand-furan prints behaved the closest to weak natural sandstone. The ceramic beads with silicate binder cores showed a fracture growth not commonly observed in natural samples, both in compression and tension. The remaining materials, generally, exhibited fracture behavior similar to natural rocks.

As mentioned, in the VPP and MJM techniques there is not a great diversity of materials. Unlike PBF, MEX, and BJT, the articles found did not report the materials based on their composition. In most cases, it was mentioned that the material was a resin, or polymer, and the specification of this material was based on the commercial product name. Despite aiding in identification, it was decided to suppress this commercial classification from Table 2 and Table 3.

By analyzing the resolution of the printers used in the documents the primary objective of this article could be achieved. However, many studies did not report a value, as shown in Table 2 and Table 3. Additionally, most of the reported values were those provided by the printer manufacturers. Ishutov & Hasiuk (2017) and Ishutov et al. (2018) were the only ones that described a process to determine the minimum pore diameter that the printers were capable of creating. BJT printers are the only ones that have their own resolution unit, dpi (droplets per inch).

Since the information mostly came from commercial sources, there is apparently a misuse of the terms accuracy, resolution, and precision, in some instances. According to VIM (2012), accuracy refers to the agreement between a measured value and the true value, resolution is defined as the smallest perceptible variation in the measured magnitude, and precision denotes the consistency of values obtained from repeated measurements. The use of the terms accuracy and resolution to express the smallest possible dimension of the printed piece was recurrently observed, with the former referring to the xy plane and the latter to the z-axis.

Printers with higher resolution faced problems of significantly lower printing speed. Li et al. (2021) used a printer with 0.5 μm resolution. It took 2.5 hours to print a cube of 0.5 mm. To print a solid cylinder with 1 mm in diameter and 2 mm in height on a printer with 1 μm resolution, Ishutov et al. (2021) reported that around 24 hours would be needed. However, by using a scaffolding technique they were able to reduce the printing time from 24 hours to 5 hours.

From a laboratory-scale perspective, printing speed is generally not considered a limitation of current 3D printing technology, as most printers are capable of producing samples within a few hours. Instead, the primary constraint of high-resolution printers lies in their limited build volume. As previously mentioned, the samples produced were only a few millimeters in size, rendering them incompatible with conventional testing equipment.

The difference in porosity between the digital and printed models was selected to measure the efficacy of the process. The four most used techniques were able to achieve small differences. Bedell et al. (2021) obtained 0.5% with MEX, Song et al. (2022) 2.9% using VPP, Almetwally & Jabbari (2021a) 2% employing BJT and Ju et al. (2022) 3% with MJM. It is important to observe that, since printed models have an inherent porosity related to the printing process, studies that used digital models with higher porosity observed a smaller difference in porosity with the printed specimen.

Hasiuk & Harding (2021) used two types of clay for printing. In addition to analyzing the printed pores, they also studied the porosities of the samples. With Iowa clay (ISU clay), they obtained an initial porosity of 36%. After the post-printing stage (in this case, firing), they reduced the porosity to 10%. Although the second clay (Limoges clay) had a higher initial porosity (39%), after the firing, the final porosity achieved (1%) was closer to that of the digital model (0%).

While some techniques, such as BJT and MEX, tend to print models with higher porosity than the digital model, others, like VPP, often create samples with lower porosity, as shown by Li et al. (2021) and Ishutov (2019), because small voids may trap residual material. Ishutov et al. (2018) reported that pores under 300 μm were initially clogged. After washing the samples, the porosity of the specimens increased by 6%. For these reasons, it is critical to perform an appropriate post-printing process.

Finally, to understand the applications, the documents were classified into three categories according to the analysis done on the printed sample. The categories adopted were structure, transport and mechanical. At first it was considered that any article that studied the structure of the printed sample (pore, porosity or granulometry, for example) fitted the first category. However, the vast majority of the documents would fall into this category. To avoid this redundancy, an article was only classified as structural analysis if it did not fit the other two categories. It was then observed that there was no

significant preference among the three groups of analysis, except for a slight predominance of transport studies.

An analysis of the digital models and techniques combination (Figure 12) showed that image-based models favored VPP and MJM, as expected. This preference can be explained by the better resolution provided by these technologies. CAD models, due to their simpler structures and lower demand of accuracy, strongly favored BJT. Regarding the papers that did not fit into either of these two categories, it was considered that there were not enough documents to draw adequate conclusions.

When examining the analysis performed in conjunction with the techniques used, no clear pattern regarding structure emerged. According to Kong et al. (2021b), the VPP technology is suited for flow experiments, while BJT should be used on mechanical experiments. A pattern observed in Figure 13 for transport and mechanical cases supports this affirmation. The first favored MJM and VPP due to their resolution. In most of these studies, greater attention was given to the structure itself rather than the material employed. On the contrary, mechanical analysis predominantly utilized BJT while scarcely employing VPP. This can be attributed to BJT's ability to use sand and clay powder as base, materials with mechanical and chemical properties more closely resembling natural cores.

Figure 14 illustrates the printing techniques used over the years. At the beginning of the analyzed period, most studies employed MEX, while no instances of BJT usage were found. In more recent documents, a shift in this trend was observed, with BJT being the most used technique. The number of studies utilizing VPP and MJM fluctuated over time but generally remained between 20% and 40%, indicating a stable trend.

Cost is a critical factor when evaluating the viability of 3D printing applications. However, this topic is rarely addressed in reviewed studies. According to Kong et al. (2021a) the cost of 3D printing has been rapidly decreasing, although high-end printers remain very expensive. In contrast, the cost of materials and supplies is generally less significant and tends to not vary substantially across most printing techniques. An alternative approach is to utilize commercial 3D printing services, which can often be more cost-effective than purchasing advanced printers.

It is interesting to highlight the rapid evolution of 3D printing in replicating the mechanical characteristics of rocks. Kong et al. (2018a) used gypsum powder to produce samples with a maximum Young's modulus of 0.3 GPa and uniaxial compressive strength (UCS) of 3.0 MPa. They concluded that their technique was only suitable for replicating fine-grained sandstones with very low strength.

Song et al. (2020) tested different materials. Their samples reached a Young's modulus of 1.3 GPa and a UCS of 9.2 MPa. They suggested that specimens made with gypsum powder could effectively reproduce the large deformation characteristics and creep failure modes of highly stressed soft rocks.

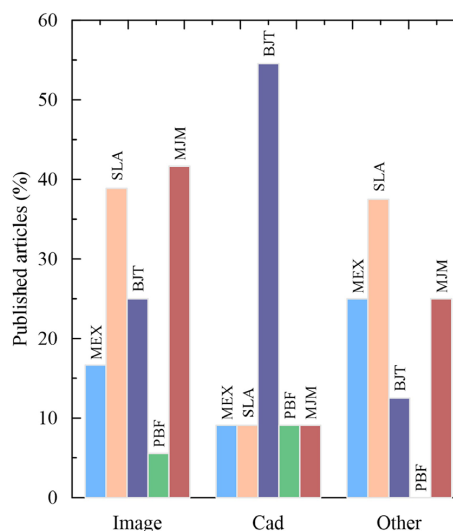


Figure 12. Digital model x printing technique.

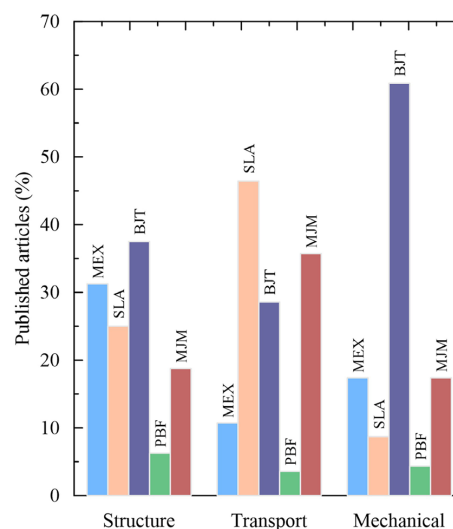


Figure 13. Analysis done versus printing technique.

Further enhancements were made by Hodder et al. (2021), who investigated the use of a larger roller during the BJT process to improve powder compaction. This adjustment yielded samples with a Young's modulus of 4.0 GPa and a UCS of 38.2 MPa.

Zhang et al. (2023) focused on post-processing techniques. They applied vacuum infiltration with phenolic resin followed by high-temperature baking. Their specimens reached a maximum Young's modulus of 6.0 GPa and a UCS of 119.4 MPa, with low coefficients of variation. The stress-strain curves also resembled those of natural high-strength, high-brittleness rocks.

Examples of acceptable reproduction of permeability. Almetwally & Jabbari (2021b) original core and printed

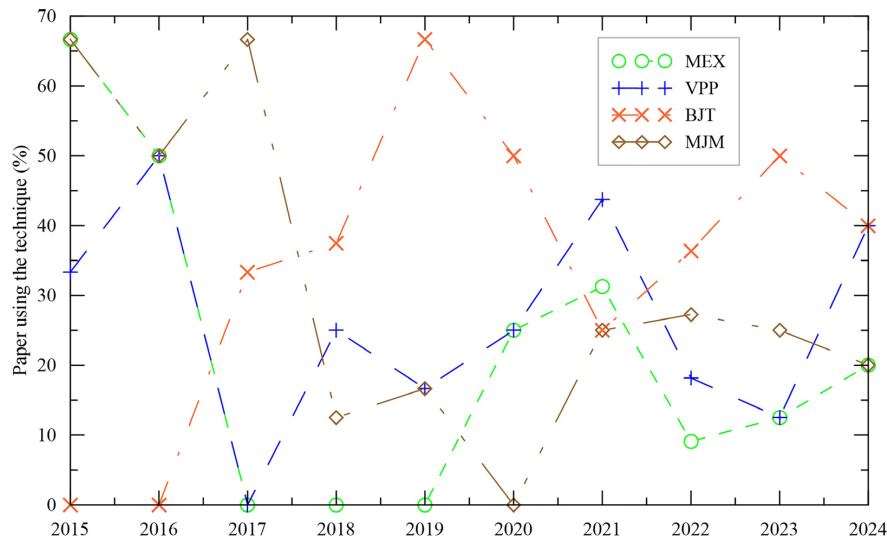


Figure 14. Printing techniques employed over the years.

sample had a permeability of 100 mD and 96 mD, respectively. Ibrahim et al. (2021) tested several samples and the average difference between digital and printed samples was around 30%. Nevertheless, the printed specimens have surface properties that can differ significantly from those of natural soils and rocks.

The contact angle of natural and printed samples can vary significantly. For example, Gates (2018) reported contact angles ranging from 37.2° for shale to 75.6° for limestone. In contrast, Ishutov (2019) and Patiño et al. (2024) tested commercial resins, the former observed values between 42.3° and 87.1° and the latter ranging from 80° to 100°. Given these wide variations, increasing attention is being directed toward techniques that modify the wettability of printed samples.

Li et al. (2020) reported initial water and water-in-oil contact angles of 87° and 123°, respectively. After coating the samples with calcite, they became completely water-wet, with the water-in-oil contact angle decreasing to 62°. Patiño et al. (2024) applied plasma treatment to reduce the contact angle of their samples, achieving reductions ranging from 30° to 60°. However, this effect is temporary, and the longevity of the treatment remains uncertain. Another aspect that requires further investigation is the uniformity of the surface modification across the sample.

6. Conclusion

The present article did a bibliometric and systematic review of the literature. By reading all the selected articles it was possible to conclude that:

- Current 3D printing technology has the capability to replicate the macrostructure of natural soils and rocks. Advanced equipment already offers resolutions on the nanoscale, enabling analysis of mesostructures and microstructures.

- Although current techniques can replicate natural pores/voids, further improvements are needed in some areas, such as accuracy, resolution, printing speed, post-processing, and available materials, for additive manufacturing to reach its full potential.
- VPP and MJM are techniques capable of achieving better resolution. However, their main drawback is that the resin used has mechanical and chemical properties that differ from those of natural soils and rocks. For this reason, VPP and MJM are suitable for reproducing structure and certain transport analyses. Although there have been successful attempts to adjust the surface properties of samples created with these techniques, the specific post-treatment that enabled this improvement still requires further studying.
- BJT technology was the most used for reproducing the mechanical properties of natural samples, as it employs powder as the base material, enabling the use of sands or clays in printing. However, BJT does not offer the same level of resolution as resin-based techniques. Additionally, most researchers were only able to replicate weak rocks. In more recent studies, however, specific post-treatment methods have enabled the production of samples that reproduce the behavior of high-strength rocks.
- MEX offers greater versatility than other techniques. However, VPP and MJM are better suited for transport studies, while BJT is preferred for mechanical studies. As a result, MEX appears to be gradually replaced by the other techniques.
- The reported results are promising, and 3D printing shows great potential as a tool for developing geoscience research. Given its rapid development, the technique is expected to become viable for laboratory applications in the near future. This could reduce

investigation costs in scenarios where sampling is expensive, enable broader use of destructive tests, and provide engineers with access to a wider range of test samples to support decision-making. However, in situ applications, particularly at large scales, remain limited and require further study and validation.

This article conducted a comprehensive bibliometric and systematic review of the literature. The review highlights the need for further exploration and refinement of 3D printing technologies in the geotechnical and geological applications. It emphasizes the importance of selecting the most appropriate printing method based on the specific research objectives and the desired level of precision, while also recognizing the ongoing necessity for technological improvements to enhance the capabilities of additive manufacturing in this field.

Acknowledgements

This study was partially financed by the Brazilian funding agencies FAPERJ and CNPq.

Declaration of interest

The authors have no conflicts of interest to declare. All co-authors have observed and affirmed the contents of the paper and there is no financial interest in reporting.

Authors' contributions

Vitor Ferreira Morales de Oliveira: conceptualization, data curation, visualization, writing – original draft. Natália Victoria dos Santos: software, writing - reviewing and editing. Marina Bellaver Corte: conceptualization, methodology, supervision, writing - reviewing and editing.

Data availability

All data produced or examined in the course of the current study are included in this article.

Declaration of use of generative artificial intelligence

Generative artificial intelligence (GenAI) tools or services were not employed in this paper. All aspects of this manuscript were developed solely by the authors, who take full responsibility for the content of this publication.

List of symbols and abbreviations

BJT	Binder Jetting
CAD	Computer Aided Design
DED	Direct Energy Deposition
MEX	Material Extrusion

MJM	Material Jetting
PBF	Powder Bed Fusion
PRISMA	Preferred Reporting Items for Systematic reviews and Meta-Analyses
SHL	Sheet Lamination
VPP	Vat Photopolymerization
WoS	Web of Science database

References

- Abdalla, H., Fattah, K.P., Abdallah, M., & Tamimi, A.K. (2021). Environmental footprint and economics of a full-scale 3D-printed house. *Sustainability (Basel)*, 13(21), 11978. <http://doi.org/10.3390/su132111978>.
- Almetwally, A.G., & Jabbari, H. (2020). Experimental investigation of 3D printed rock samples replicas. *Journal of Natural Gas Science and Engineering*, 76, 103192. <http://doi.org/10.1016/j.jngse.2020.103192>.
- Almetwally, A.G., & Jabbari, H. (2021a). CO2 huff-n-puff experimentation and numerical simulation for 3D printed rock samples. *International Journal of Heat and Mass Transfer*, 180, 121798. <http://doi.org/10.1016/j.ijheatmasstransfer.2021.121798>.
- Almetwally, A.G., & Jabbari, H. (2021b). 3D-printing replication of porous media for lab-scale characterization research. *ACS Omega*, 6(4), 2655-2664. PMID:33553883. <http://doi.org/10.1021/acsomega.0c04825>.
- Anjekar, I.S., Wales, S., & Beckingham, L.E. (2020). Fused Filament Fabrication 3-D Printing of Reactive Porous Media. *Geophysical Research Letters*, 47(9), e2020GL087665. <http://doi.org/10.1029/2020GL087665>.
- Aria, M., & Cuccurullo, C. (2017). bibliometrix: an R-tool for comprehensive science mapping analysis. *Journal of Informetrics*, 11(4), 959-975. <http://doi.org/10.1016/j.joi.2017.08.007>.
- Arrieta-Escobar, J.A., Derrien, D., Ouvrard, S., Asadollahi-Yazdi, E., Hassan, A., Boly, V., Tinet, A.-J., & Dignac, M.-F. (2020). 3D printing: an emerging opportunity for soil science. *Geoderma*, 378, 114588. <http://doi.org/10.1016/j.geoderma.2020.114588>.
- ASTM 52900. (2021). *Additive Manufacturing-General Principles-Terminology*. ASTM International, West Conshohocken, PA. <http://doi.org/10.1520/F3177-21>.
- Bacher, M., Schwen, A., & Koestel, J. (2015). Three-dimensional printing of macropore networks of an undisturbed soil sample. *Vadose Zone Journal*, 14(2), 1-10. <http://doi.org/10.2136/vzj2014.08.0111>.
- Bedell, R., Hassan, A., Tinet, A.-J., Arrieta-Escobar, J., Derrien, D., Dignac, M.-F., Boly, V., Ouvrard, S., & Pearce, J.M. (2021). Open-Source script for design and 3d printing of porous structures for soil science. *Technologies*, 9(3), 67. <http://doi.org/10.3390/technologies9030067>.
- Ceccanti, F., Dini, E., De Kestelier, X., Colla, V., & Pambaguian, L. (2010). 3D printing technology for a moon outpost exploiting lunar soil. In *61st International Astronautical*

- Congress 2010, IAC 2010 (pp. 8812-8820). Italy. European Space Agency (ESA).
- Chakraborty, P.P., & Derby, M.M. (2024). Analysis of drying front propagation and coupled heat and mass transfer during evaporation from additively manufactured porous structures under a solar flux. *ASME Journal of Heat and Mass Transfer*, 146(2), 021602. PMID:38111632. <http://doi.org/10.1115/1.4063766>.
- Cruz-Maya, J. A., Martínez-Mendoza, L. C., Sanchez-Silva, F., Rosas-Flores, J. A., & Jan-Roblero, J. (2022). Three-dimensional additive manufacturing of artificial oil reservoir rock core plugs for core flooding experimental tests. *3D Printing and Additive Manufacturing*, 9(4), 233-243. <http://doi.org/10.1089/3dp.2021.0149>.
- Cruz-Maya, J.A., Mendoza-de la Cruz, J.L., Martínez-Mendoza, L.C., Sánchez-Silva, F., Rosas-Flores, J.A., & Jan-Roblero, J. (2023). Three-dimensional printing of synthetic core plugs as an alternative to natural core plugs: experimental and numerical study. *Processes (Basel, Switzerland)*, 11(9), 2530. <http://doi.org/10.3390/pr11092530>.
- Dal Ferro, N., & Morari, F. (2015). From real soils to 3D-printed soils: reproduction of complex pore network at the real size in a silty-loam soil. *Soil Science Society of America Journal*, 79(4), 1008-1017. <http://doi.org/10.2136/sssaj2015.03.0097>.
- Dande, S., Stewart, R.R., & Dyaury, N. (2021). Effect of fluids on the elastic properties of 3d-printed anisotropic rock models. *Petrophysics*, 62(5), 537-552. <http://doi.org/10.30632/PJV62N5-2020a7>.
- Dimou, A. P., Menke, H.P., & Maes, J. (2022). Benchmarking the viability of 3D printed micromodels for single phase flow using particle image velocimetry and direct numerical simulations. *Transport in Porous Media*, 141(2), 279-294. <http://doi.org/10.1007/s11242-021-01718-8>.
- Elayed, M., El-Husseiny, A., Kwak, H., Hussaini, S.R., & Mahmoud, M. (2021). New technique for evaluating fracture geometry and preferential orientation using pulsed field gradient nuclear magnetic resonance. *SPE Journal*, 26(05), 2880-2893. <http://doi.org/10.2118/205505-PA>.
- Ferrari, A., Rosone, M., La Rosa, S., & Sapienza, G. (2022). Microstructural characterization of a 3D-printed soil. *Soils and Rocks*, 45(4), 1-6. <http://doi.org/10.28927/SR.2022.005422>.
- Gao, Y., Wu, T., & Zhou, Y. (2021). Application and prospective of 3D printing in rock mechanics: A review. *International Journal of Minerals Metallurgy and Materials*, 28(1), 1-17. <http://doi.org/10.1007/s12613-020-2119-8>.
- Gates, C.H. (2018). *Estimating wettability of rock fracture surfaces from contact angle and roughness measurements* [Master's dissertation, University of Tennessee]. University of Tennessee 's repository. Retrieved in July 29, 2024, from https://trace.tennessee.edu/utk_gradthes/5109/
- Gomez, J.S., Chalaturnyk, R.J., & Zambrano-Narvaez, G. (2019). Experimental investigation of the mechanical behavior and permeability of 3d printed sandstone analogues under triaxial conditions. *Transport in Porous Media*, 129(2), 541-557. <http://doi.org/10.1007/s11242-018-1177-0>.
- Goral, J., & Deo, M. (2020). Nanofabrication of synthetic nanoporous geomaterials: from nanoscale-resolution 3D imaging to nano-3D-printed digital (shale) rock. *Scientific Reports*, 10(1), 21596. PMID:33299052. <http://doi.org/10.1038/s41598-020-78467-z>.
- Haddaway, N.R., Page, M.J., Pritchard, C.C., & McGuinness, L.A. (2022). PRISMA2020: an R package and Shiny app for producing PRISMA 2020-compliant flow diagrams, with interactivity for optimised digital transparency and Open Synthesis. *Campbell Systematic Reviews*, 18(2), e1230. PMID:36911350. <http://doi.org/10.1002/cl2.1230>.
- Hasheminezhad, A., Ceylan, H., Kim, S., & Tutumluer, E. (2025). Evaluation of 3D-printed model geogrids and composite geosynthetics made from recycled plastics: bridging laboratory insights with field performance. *Construction & Building Materials*, 465, 1-15. <http://doi.org/10.1016/j.conbuildmat.2025.140258>.
- Hasiuk, F., & Harding, C. (2021). 3D printing mudrocks: experiments in validating clay as a build material for 3d printing porous micromodels. *Petrophysics*, 62(5), 486-499. <http://doi.org/10.30632/PJV62N5-2020a4>.
- Hasiuk, F., Ishutov, S., & Pacyga, A. (2018). Validating 3D-printed porous proxies by tomography and porosimetry. *Rapid Prototyping Journal*, 24(3), 630-636. <http://doi.org/10.1108/RPJ-06-2017-0121>.
- Hasiuk, F.J. (2019). Testing bulk properties of powder-based 3d-printed reservoir rock proxies. *Transport in Porous Media*, 129(2), 501-520. <http://doi.org/10.1007/s11242-018-1221-0>.
- Head, D., & Vanorio, T. (2016). Effects of changes in rock microstructures on permeability: 3-D printing investigation. *Geophysical Research Letters*, 43(14), 7494-7502. <http://doi.org/10.1002/2016GL069334>.
- Hodder, K.J., Craplewe, K., Ishutov, S., & Chalaturnyk, R. (2021). Binder saturation as a controlling factor for porosity variation in 3D-printed sandstone. *Petrophysics*, 62(5), 450-462. <http://doi.org/10.30632/PJV62N5-2020a1>.
- Hodder, K.J., Sanchez-Barra, A.J., Ishutov, S., Zambrano-Narvaez, G., & Chalaturnyk, R.J. (2022). Increasing density of 3D-printed sandstone through compaction. *Energies*, 15(5), 1813. <http://doi.org/10.3390/en15051813>.
- Huang, L., Stewart, R.R., Dyaury, N., & Baez-Franceschi, J. (2016). 3D-printed rock models: elastic properties and the effects of penny-shaped inclusions with fluid substitution. *Geophysics*, 81(6), D669-D677. <http://doi.org/10.1190/geo2015-0655.1>.
- Ibrahim, E.R., Jouini, M.S., Bouchaala, F., & Gomes, J. (2021). Simulation and validation of porosity and permeability of synthetic and real rock models using three-dimensional printing and digital rock physics. *ACS Omega*, 6(47),

- 31775-31781. PMID:34870000. <http://doi.org/10.1021/acsomega.1c04429>.
- International Vocabulary of Metrology - VIM. (2012). *International vocabulary of metrology: basic and general concepts and associated terms (VIM)* (3rd ed.). International Bureau of Weights and Measures, JCGM.
- Ishutov, S. (2019). Establishing framework for 3d printing porous rock models in curable resins. *Transport in Porous Media*, 129(2), 431-448. <http://doi.org/10.1007/s11242-019-01297-9>.
- Ishutov, S., & Hasiuk, F.J. (2017). 3D printing berea sandstone: testing a new tool for petrophysical analysis of reservoirs. *Petrophysics*, 58(6), 592-602.
- Ishutov, S., Hasiuk, F.J., Fullmer, S.M., Buono, A.S., Gray, J.N., & Harding, C. (2017). Resurrection of a reservoir sandstone from tomographic data using three-dimensional printing. *AAPG Bulletin*, 101(9), 1425-1443. <http://doi.org/10.1306/11111616038>.
- Ishutov, S., Hasiuk, F.J., Jobe, D., & Agar, S. (2018). Using resin-based 3D printing to build geometrically accurate proxies of porous sedimentary rocks. *Ground Water*, 56(3), 482-490. PMID:28960285. <http://doi.org/10.1111/gwat.12601>.
- Ishutov, S., Hodder, K., Chalaturnyk, R., & Zambrano-Narvaez, G. (2021). Replication of carbonate reservoir pores at the original size using 3D printing. *Petrophysics*, 62(5), 477-485. <http://doi.org/10.30632/PJV62N5-2020a3>.
- Jouini, M.S., Gomes, J.S., Tembely, M., & Ibrahim, E.R. (2021). Upscaling strategy to simulate permeability in a carbonate sample using machine learning and 3D printing. *IEEE Access : Practical Innovations, Open Solutions*, 9, 90631-90641. <http://doi.org/10.1109/ACCESS.2021.3091772>.
- Ju, Y., Ren, Z., Li, X., Wang, Y., Mao, L., & Chiang, F.-P. (2019). Quantification of hidden whole-field stress inside porous geomaterials via three-dimensional printing and photoelastic testing methods. *Journal of Geophysical Research. Solid Earth*, 124(6), 5408-5426. <http://doi.org/10.1029/2018JB016835>.
- Ju, Y., Ren, Z., Mao, L., & Chiang, F.-P. (2018). Quantitative visualisation of the continuous whole-field stress evolution in complex pore structures using photoelastic testing and 3D printing methods. *Optics Express*, 26(5), 6182-6201. PMID:29529811. <http://doi.org/10.1364/OE.26.006182>.
- Ju, Y., Xi, C., Zheng, J., Gong, W., Wu, J., Wang, S., & Mao, L. (2022). Study on three-dimensional immiscible water-oil two-phase displacement and trapping in deformed pore structures subjected to varying geostress via in situ computed tomography scanning and additively printed models. *International Journal of Engineering Science*, 171, 103615. <http://doi.org/10.1016/j.ijengsci.2021.103615>.
- Ju, Y., Zheng, Z., Xie, H., Lu, J., Wang, L., & He, K. (2017). Experimental visualisation methods for three-dimensional stress fields of porous solids. *Experimental Techniques*, 41(4), 331-344. <http://doi.org/10.1007/s40799-017-0178-1>.
- Kitao, T., Fukumoto, Y., Fujisawa, K., Jewel, A., & Murakami, A. (2021). Validation of LBM simulation of saturated seepage flow through 3D-printed homogeneous porous medium for fluid-particle coupled analysis. *Acta Geotechnica*, 16(8), 2643-2656. <http://doi.org/10.1007/s11440-021-01210-z>.
- Kong, L., Ostadhassan, M., Li, C., & Tamimi, N. (2018a). Can 3-D printed gypsum samples replicate natural rocks? An experimental study. *Rock Mechanics and Rock Engineering*, 51(10), 3061-3074. <http://doi.org/10.1007/s00603-018-1520-3>.
- Kong, L., Ostadhassan, M., Li, C., & Tamimi, N. (2018b). Pore characterization of 3D-printed gypsum rocks: a comprehensive approach. *Journal of Materials Science*, 53(7), 5063-5078. <http://doi.org/10.1007/s10853-017-1953-1>.
- Kong, L., Ostadhassan, M., Hou, X., Mann, M., & Li, C. (2019a). Microstructure characteristics and fractal analysis of 3D-printed sandstone using micro-CT and SEM-EDS. *Journal of Petroleum Science Engineering*, 175, 1039-1048. <http://doi.org/10.1016/j.petrol.2019.01.050>.
- Kong, L., Ostadhassan, M., Liu, B., Li, C., & Liu, K. (2019b). Multifractal characteristics of MIP-based pore size distribution of 3D-printed powder-based rocks: a study of post-processing effect. *Transport in Porous Media*, 129(2), 599-618. <http://doi.org/10.1007/s11242-018-1152-9>.
- Kong, L., Ishutov, S., Hasiuk, F., & Xu, C. (2021a). 3D printing for experiments in petrophysics, rock physics, and rock mechanics: a review. *SPE Reservoir Evaluation & Engineering*, 24(04), 721-732. <http://doi.org/10.2118/206744-PA>.
- Kong, L., Ostadhassan, M., Liu, B., Eshraghi, M., Li, C., Navarro, M., Zhang, Y., & Wei, H. (2021b). A comparison of three-dimensional-printed porous rocks with nano x-ray computed tomography: silica sand, gypsum powder, and resin. *AAPG Bulletin*, 105(11), 2245-2261. <http://doi.org/10.1306/08142019028>.
- Lamandé, M., Schjonning, P., Dal Ferro, N., & Morari, F. (2021). Soil pore system evaluated from gas measurements and CT images: a conceptual study using artificial, natural and 3D-printed soil cores. *European Journal of Soil Science*, 72(2), 769-781. <http://doi.org/10.1111/ejss.12999>.
- Lesueur, M., Poulet, T., & Veveakis, M. (2021). Predicting the yield strength of a 3D printed porous material from its internal geometry. *Additive Manufacturing*, 44, 102061. <http://doi.org/10.1016/j.addma.2021.102061>.
- Lesueur, M., Zhang, X., Poulet, T., & Veveakis, M. (2023). Predicting the yield stress of geomaterials from their microstructure. In E. Pasternak & A. Dyskin (Eds.), *Multiscale Processes of Instability, Deformation and Fracturing in Geomaterials. IWBDG 2022* (Springer Series in Geomechanics and Geoengineering, pp. 205-211). Springer. http://doi.org/10.1007/978-3-031-22213-9_21.
- Li, A., Zhang, S., Xu, C., Zhao, X., & Zhang, X. (2021). 3D printing of true pore-scale berea sandstone and digital

- rock verification. *SPE Journal*, 26(6), 3719-3724. <http://doi.org/10.2118/205383-PA>.
- Li, H., Raza, A., Ge, Q., Lu, J.-Y., & Zhang, T. (2020). Empowering microfluidics by micro-3D printing and solution-based mineral coating. *Soft Matter*, 16(29), 6841-6849. PMID:32638816. <http://doi.org/10.1039/D0SM00958J>.
- Maraveas, C., Kyrtopoulos, I.V., & Arvanitis, K.G. (2024). Evaluation of the viability of 3D printing in recycling polymers. *Polymers*, 16(8), 1104. PMID:38675022. <http://doi.org/10.3390/polym16081104>.
- Matsumura, S., Kawamura, S., Kandpal, L., & Vangla, P. (2023). 3D printed porous particle and its geotechnical properties. *Acta Geotechnica*, 18(11), 5735-5753. <http://doi.org/10.1007/s11440-023-01981-7>.
- Moher, D., Liberati, A., Tetzlaff, J., & Altman, D.G., & PRISMA Group. (2009). Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. *Annals of Internal Medicine*, 151(4), 264-269, W64. PMID:19622511. <http://doi.org/10.7326/0003-4819-151-4-200908180-00135>.
- Oskolkov, A.A., Kochnev, A.A., Krivoshechekov, S.N., & Savitsky, Y.V. (2024). Real-size reconstruction of porous media using the example of fused filament fabrication 3D-printed rock analogues. *Journal of Manufacturing and Materials Processing*, 8(3), 104. <http://doi.org/10.3390/jmmp8030104>.
- Patino, J.E., Miele, F., Perez, A.J., Kanavas, Z., Dughi, M.L., & Morales, V.L. (2024). Replication of soil analogues at the original scale by 3D printing: quantitative assessment of accuracy and repeatability of the pore structural heterogeneity. *Advances in Water Resources*, 192, 104795. <http://doi.org/10.1016/j.advwatres.2024.104795>.
- Perras, M.A., & Vogler, D. (2019). Compressive and tensile behavior of 3d-printed and natural sandstones. *Transport in Porous Media*, 129(2), 559-581. <http://doi.org/10.1007/s11242-018-1153-8>.
- Richardson, W.S., Wilson, M.C., Nishikawa, J., & Hayward, R.S. (1995). The well-built clinical question: a key to evidence-based decisions. *ACP Journal Club*, 123(3), A12-A13. PMID:7582737. <http://doi.org/10.7326/ACPJC-1995-123-3-A12>.
- Santiago, V., Zabala, F.G., Sanchez-Barra, A.J., Deisman, N., Chalaturnyk, R.J., Zhong, R., & Hurter, S. (2022). Experimental investigation of the flow properties of layered coal-rock analogues. *Chemical Engineering Research & Design*, 186, 685-700. <http://doi.org/10.1016/j.cherd.2022.08.046>.
- Schafrik, S., & Millar, D.L. (2015). Verification of a CFD code use for air flow simulations of fractured and broken rock. *Applied Thermal Engineering*, 90, 1131-1143. <http://doi.org/10.1016/j.applthermaleng.2015.03.021>.
- Shao, Y., Kim, J., Yang, J., Song, J.J., & Moon, J. (2024). Experimental study on strength enhancement and porosity variation of 3d-printed gypsum rocks: insights on vacuum infiltration post-processing. *Rock Mechanics and Rock Engineering*, 57(9), 6763-6786. <http://doi.org/10.1007/s00603-024-03913-7>.
- Shao, Y., Yang, J., Kim, J., Song, J.-J., Moon, J., & Han, J. (2023). A comprehensive experimental study on mechanical anisotropy and failure mode of 3d printed gypsum rocks: from composition and microstructure to macroscopic mechanical properties response. *Rock Mechanics and Rock Engineering*, 56(9), 6503-6528. <http://doi.org/10.1007/s00603-023-03401-4>.
- Silva, A.V., Solis, D.M., Innocentini, M.D.M., & Foggatto, J.A. (2023). Preliminary study for permeability adjustment of triaxial porous ceramic media obtained by binder jetting. *Journal of Manufacturing Processes*, 87, 36-45. <http://doi.org/10.1016/j.jmapro.2022.12.058>.
- Song, R., Wang, Y., Ishutov, S., Zambrano-Narvaez, G., Hodder, K.J., Chalaturnyk, R.J., Sun, S., Liu, J., & Gamage, R.P. (2020). A comprehensive experimental study on mechanical behavior, microstructure and transport properties of 3D-printed rock analogs. *Rock Mechanics and Rock Engineering*, 53(12), 5745-5765. <http://doi.org/10.1007/s00603-020-02239-4>.
- Song, R., Wang, Y., Sun, S., & Liu, J. (2021). Characterization and microfabrication of natural porous rocks: from micro-CT imaging and digital rock modelling to micro-3D-printed rock analogs. *Journal of Petroleum Science Engineering*, 205, 108827. <http://doi.org/10.1016/j.petrol.2021.108827>.
- Song, R., Wang, Y., Tang, Y., Peng, J., Liu, J., & Yang, C. (2022). 3D Printing of natural sandstone at pore scale and comparative analysis on micro-structure and single/two-phase flow properties. *Energy*, 261, 125226. <http://doi.org/10.1016/j.energy.2022.125226>.
- Tang, D., Hao, L., Li, Y., Xiong, W., Sun, T., & Yan, X. (2018). Investigation of wax-based barite slurry and deposition for 3D printing landslide model. *Composites. Part A, Applied Science and Manufacturing*, 108, 99-106. <http://doi.org/10.1016/j.compositesa.2018.02.007>.
- van Eck, N.J., & Waltman, L. (2010). Software survey: VOSviewer, a computer program for bibliometric mapping. *Scientometrics*, 84(2), 523-538. PMID:20585380. <http://doi.org/10.1007/s11192-009-0146-3>.
- Wang, Y., Li, S., Song, R., Liu, J., Ye, M., Peng, S., & Deng, Y. (2022). Effects of grain size and layer thickness on the physical and mechanical properties of 3D-printed rock analogs. *Energies*, 15(20), 7641. <http://doi.org/10.3390/en15207641>.
- Wollner, U., Vanorio, T., & Kiss, A.M. (2018). The effect of fluid and solid properties on the auxetic behavior of porous materials having rock-like microstructures. *International Journal of Solids and Structures*, 130-131, 211-219. <http://doi.org/10.1016/j.ijsolstr.2017.09.033>.
- Wu, H., Ju, Y., Han, X., Ren, Z., Sun, Y., Zhang, Y., & Han, T. (2022a). Size effects in the uniaxial compressive properties of 3D printed models of rocks: an experimental

- investigation. *International Journal of Coal Science & Technology*, 9(1), 83. <http://doi.org/10.1007/s40789-022-00556-3>.
- Wu, T., Zhao, H., Xu, Q., & Zhao, Y. (2022b). Optimal analysis of material ratio for artificial rock by 3D printing technique. *Geomechanics and Geoengineering*, 17(1), 260-268. <http://doi.org/10.1080/17486025.2020.1739752>.
- Yu, C., & Tian, W. (2024). Application and prospective of sand-type 3D printing material in rock mechanics: a review. *Rapid Prototyping Journal*, 30(6), 1057-1069. <http://doi.org/10.1108/RPJ-12-2023-0427>.
- Yu, C., Tian, W., & Wang, X. (2024). Microstructure and mechanical behavior of 3D printed rock-like specimens based on different post-processing methods. *International Journal of Rock Mechanics and Mining Sciences*, 180, 105822. <http://doi.org/10.1016/j.ijrmms.2024.105822>.
- Zhang, K., & Li, N. (2022). A new method to replicate high-porosity weak rocks subjected to cyclic freezing-thawing: Sand 3D printing and digital image correlation explorations. *International Journal of Rock Mechanics and Mining Sciences*, 157, 105174. <http://doi.org/10.1016/j.ijrmms.2022.105174>.
- Zhang, K., Zhang, K., Ye, J., Liu, X., & Fan, W. (2023). An improved sand 3D printing method for better reproduction of high-strength and high-brittleness rock mechanical properties is proposed. *Journal of Materials Research and Technology*, 26, 5037-5054. <http://doi.org/10.1016/j.jmrt.2023.08.204>.
- Zhao, X., Cai, X., Zhou, X., Lai, Z., Zhong, Q., Chu, Z., Zhou, G., & Li, H. (2023). Experimental study on compression and torsion fracture within 3D printed cementation-weak and porosity-high sandstones. *Geofluids*, 2023, 1-18. <http://doi.org/10.1155/2023/6051378>.
- Zhao, X., Liu, Y., Zou, C., He, L., Che, P., & Li, J. (2024). Physical simulation of brittle rocks by 3D printing techniques considering cracking behaviour and permeability. *Applied Sciences (Basel, Switzerland)*, 14(1), 344. <http://doi.org/10.3390/app14010344>.
- Zhong, H., & Zhang, M. (2022). 3D printing geopolymers: a review. *Cement and Concrete Composites*, 128, 104455. <http://doi.org/10.1016/j.cemconcomp.2022.104455>.