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ABSTRACT

The soil, at the interface between geosphere, biosphere, and atmosphere, is a particularly challenging object to study. The ecological and environmental impacts of soil functioning encourage soil scientists to exploit new technologies to generate new data or develop new research protocols. Among these technologies, 3D printing is a promising technology for improving the understanding of soils. The general principle of 3D printing is to build parts by adding materials layer by layer following a three-dimensional solid model. The 3D printing technology makes it possible to produce almost any geometrically complex shape or feature in a wide range of materials. Its interest lies in its ability to produce customized objects easily and rapidly in an endlessly reproducible 3D-arrangement. A large number of techniques and materials are available, which differ in their principles, advantages, and shortcomings.

In this article, we present the main challenges and opportunities of using 3D printing in soil science. To this end, we present a review of the literature from 2000 to 2019 to identify and understand recent applications of 3D printing in this field. We first describe applications such as the manufacturing of agricultural equipment and laboratory devices in soil science, the development of new construction materials, or the geotechnical characterization of soil as a construction base. However, none of these applications requires replication of the soil functional properties as opposed to applications that would be dedicated to improving the understanding of soil functioning. We detail here the challenges and opportunities of building soil models that reproduce its physical, chemical, biological properties, and its dynamics in contact with living organisms.

Despite the remarkable and rapid progress made in the development of 3D printing in recent years, this technology is still underused in the field of soil science. In particular, very few applications focus on the functioning of the soil itself as an ecological compartment. Indeed, several technical limitations have still to be overcome. 3D printed objects must be biocompatible, chemically and mechanically stable, and must be spatially resolved on the microscale. Many efforts are being made by the 3D printing community to push these boundaries. This paves the way for the wider use of 3D printing in soil science. In the near future, the availability of additive manufactured soil models, with strict and controlled composition and structure, will provide researchers with an irreplaceable opportunity to conduct reproducible experiments and better understand soil functioning factors.

KEYWORDS. 3D Printing; Additive Manufacturing; Soil functions; Soil structure; Artificial soil

1. INTRODUCTION

Soils are a key environmental compartment providing many products, which derive mainly from their agricultural use, and other services useful to human well-being (Commission of the European Communities, 2006). Different soil properties, such as their physical structure, their composition in soil organic matter (SOM), minerals, plant and micro-organisms, and their spatial arrangement, determine soil health. Healthy soils can deliver tangible economic and environmental benefits to farmers, businesses, and human communities (FAO, 2015). They have the capacity to respond to agricultural intervention and support for generations both the optimal biomass production and the provision of other ecosystem services (Kibblewhite et al., 2008).

Soil is a complex system in terms of geometry and materials, which leads to high spatial variations of soil structure and composition from the microscopic scale to the field, regional, and global extents. This spatial diversity and variability depend on land use, soil management, agricultural practices, as well as soil types and climate. Soil diversity is a key factor influencing ecological processes and soil functioning. Because of this high variability, it is difficult to understand individual soil type functioning and to compare the functions and services offered by different soils. To address these challenges, soil scientists need to reach out to other scientific disciplines (Keesstra et al., 2016), looking for innovative approaches and solutions (Hu and Jiang, 2017). In this sense, 3D printing is a promising tool in soil science due to its capability to rapidly produce complex, endlessly replicable, and customizable geometrical structures, in a wide range of controlled materials (Behm et al., 2018).

Three-dimensional (3D) printing, also known as additive manufacturing, is defined as the process of joining materials to make objects layer upon layer from 3D model data (Bikas et al., 2016). At its beginning in the 1980s, the first applications were prototyping, but in the following decades, the manufacturing technologies and materials transformed, and new fields of application appeared (Leutenecker-Twelsiek et al., 2016). Today, a large number of technologies have been developed for 3D printing, which differs in the way layers are deposited to create parts, changing the operating principle and the used material.

3D printing is driving major innovations in many areas, including aeronautics, medicine (Bartolo et al., 2012; Chia and Wu, 2015; Kang et al., 2016; Rengier et al., 2010), manufacturing and engineering (Doubrovski et al., 2011; Leutenecker-Twelsiek et al., 2016; Postiglione et al., 2015; Shahrubudin et al., 2019; Sossou et al., 2018; Yao et al., 2017; Zhang et al., 2016), art (Séquin, 2015; Balletti et al., 2017; Mitterberger and Derme, 2019; Derme and Mitterberger, 2020), education (Kostakis et al., 2015; Wood et al., 2017), building (Ahmed et al., 2016; Duballet et al., 2017), food (Godoi et al., 2016; Sun et al., 2015; Vancauwenberghe et al., 2017), and especially in customized production (Asadollahi-Yazdi et al., 2016). Nevertheless, soil science is a recent field of application of 3D printing and further development and application should impact the way researchers study soils within their ecosystems (Hu and Jiang, 2017). The development of 3D-printed objects adapted to the soil science field should facilitate, for example, the comparison of pedoclimatic conditions and support research for the understanding of soil functioning.

This paper focuses on the past and future achievements associated with 3D printing manufacturing use in soil science. First, we described the currently available 3D printing techniques and performed a bibliometric study of the studies, which used any of these techniques for soil-related purposes. Then, we identified the added value of 3D printing technologies for the investigated processes and functions and the possible constraints they generate. Finally, we explored the opportunities and challenges arising from the deployment of 3D printing in soil research to evaluate to what extent it meets the needs of soil science challenges and to encourage soil scientists to seize this new exciting and vast area of research.

2. OVERVIEW OF 3D PRINTING TECHNIQUES

Producing an object with 3D printing necessitates the use of a specific technology, applied to a material or materials, using different energy sources. In the following sections, the combination of a specific technology, material, and energy source will be referred to as 3D printing « method ». Each method has its advantages and drawbacks in economic, technical, and environmental terms (Asadollahi-Yazdi et al., 2018; Ford and Despeisse, 2016). Table 1 summarizes the different processes, technologies, and materials, as well as their characteristics, strengths, and limitations.

2.1. PROCESSES AND TECHNOLOGIES

According to ASTM International standards, 3D printing technologies are classified into seven process categories (Gao et al., 2015). The first category of processes, material extrusion, is based on the construction of the object by material extrusion through a nozzle. It comprises the use of melted plastics (fused deposition modeling - FDM) or gel-like materials followed in general by a drying step (direct ink writing - DIW). In a second group, called directed energy deposition, metals are melted using different high-energy sources, i.e. lasers for Laser Engineered Net Shaping - LENS, or electron beams for Electron Beam Welding - EBW technologies. In the third category of processes, called material jetting, droplets of a liquid (photopolymer or wax) are deposited and then hardened with UV-light, in technologies like polyjet or inkjet printing (MJM). In the fourth group, called powder bed fusion, the object is built by sintering or melting powdered materials thanks to a high-energy source, such as a laser, as in Selective Laser Sintering (SLS) and Selective Laser Melting (SLM) or an electron beam, as in Electron Beam Melting (EBM). In the fifth category, VAT polymerization, the solidification of a liquid material occurs through polymerization of plastic or resin using a light source, for example, lasers in the case of stereolithography technology (SLA). In the sixth group, binder jetting, the conformation of the object is achieved through binding with chemicals in what is called indirect inkjet printing or 3DP technologies. In the last category of processes, sheet lamination, the object is built by cutting and assembling solid materials through compaction (laminated object manufacturing, LOM). Some of the aforementioned technologies need a post-processing step, such as drying or polishing. The main considerations for choosing the appropriate technology are, in general terms, speed, cost of the printed prototype, as well as cost and spatial resolution range of the available materials (Bikas et al., 2016).

In addition to the seven process categories described above, bioprinting appears a supplementary group of 3D printing techniques based on the deposition of biomaterials (like DIW, MJM, and SLA), either encapsulating cells or loaded with cells later on, at the micrometer scale, to form subtle structures comparable to living tissues (Derakhshanfar et al., 2018). It has recently been extensively developed in medical science for printing functional solid organs according to the manufacturing-specific production capability.

2.2. MATERIALS

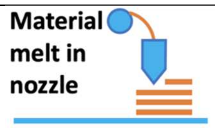
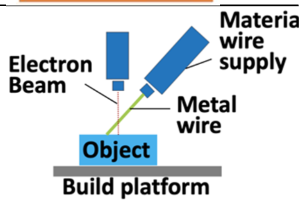
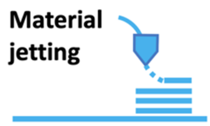
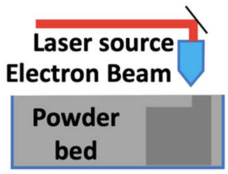
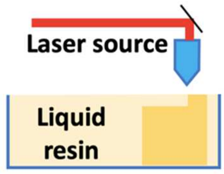
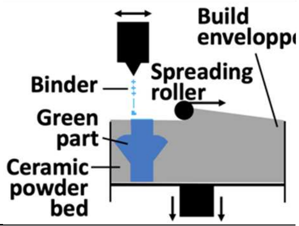
Each 3D printing technology can be implemented with a specific material, adapted to the desired application (third column in Table 1). Different types of printable materials are available: plastics - divided in thermally stable plastics (e.g. epoxy, polyesters, silicone-based materials) and those modifiable by temperature (e.g. polyamide, polyethylene, polypropylene or polylactic acid, PLA); silicon-based materials (clay, ceramics, glass, etc.); metals and others, such as graphene-based and biomaterials (Thompson et al., 2016). This last group of materials is gaining considerable attention due to the rising interest in a “bio-based society” (Dai et al., 2019; Håkansson et al., 2016). Some applications (medicine, ecology, etc.) require biocompatible materials, which is not the case for most existing materials in 3D printing. Increasing concern with environmental issues associated with the use of fossil-based resources can also impact the choice of more sustainable (Dai et al., 2019; Xu et al., 2018). Biomaterials can be implemented with different technologies, such as direct ink writing, inkjet, stereolithography, or laser-assisted bioprinting.

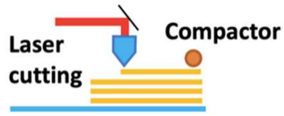
Many natural polymers (cellulose, lignin, pectin, alginates) can be used to build the biocompatible supports that receive the living cells. Recent developments such as multi-material printing using different hydrogels together and combining different printing technologies are some of the most important technological advances that can help to develop the applications of bioprinting in tissue engineering (Dai et al., 2019).

Besides bioprinting applications requiring biocompatible materials, cellulosic materials are the most common bio-based materials in many other applications (Liu et al., 2019). Indeed, cellulose and its derivatives are sustainable, almost inexhaustible, and biodegradable polymeric raw materials that meet the rising demand for environmentally friendly products (Dai et al., 2019; Klemm et al., 2005).

This group of materials includes cellulose ethers/esters, microcrystalline cellulose, nano cellulose, etc. In soils, cellulose plays a significant role, as it is the principal component of plants. They are a good alternative to plastic-derived materials since they provide most of the mechanical properties required for materials used in 3D printing technologies (Li et al., 2018). In various 3D printing methods, cellulose and its derivatives are used as substrates, building blocks, viscosity modifiers, binders, excipients, plasticizers, matrices, fillers, and reinforcing agents (Dai et al., 2019). There is also a big potential for cellulosic materials to be the precursors for smart cost-effective materials, which could be assembled in a controlled way to respond to external stimuli, such as temperature, light or other environmental factors, and thus evolve – in what is called 4D printing (André, 2017; Mulakkal et al., 2016).

Table 1. Classification of 3D printing processes (Asadollahi-Yazdi et al., 2016; Bikas et al., 2016; Gao et al., 2015; Li et al., 2015; Thompson et al., 2016). Some illustrations are reprinted in part with permission from Bikas et al. Copyright © 2015, Springer Nature (Creative Commons CC BY).

Process category	Technology	Material type	Example materials	Strengths/ Downsides	Process schematic
Material Extrusion	Fused Deposition Modeling (FDM)	Thermoplastic polymers	Polyamide, Acrylonitrile Butadiene Styrene, Polylactic Acid	Inexpensive extrusion machine Multi-material printing Limited part resolution Poor surface finish	
	Direct Ink Writing (DIW)	Aqueous slurries and dispersions	Cellulose-based hydrogels	Ideal for biomaterials Maintaining structural integrity during drying	
Direct Energy Deposition	Electron Beam Welding (EBW) Laser Engineered Net Shaping (LENS)	Molten metal powder	Steel Titanium Alloys, Cobalt Chromium	Repair of damaged/ worn parts Functionality graded material printing Require post-processing machine	
Material Jetting	Polyjet/Inkjet Printing (MJM)	Thermally stable or unstable plastics	Photopolymers Wax	Multi-material printing High surface finish Low strength material	
Powder Bed Fusion	Selective Laser Sintering (SLS)	Polyamides / Polymers	Nylon, Polystyrene	High accuracy and details Fully dense parts High specific strength and stiffness Powder handling and recycling Support and structure	
	Selective Laser Melting (SLM)	Atomized metal powder, Ceramic powder	Steel, Titanium alloys, Cobalt chromium, Alumina, Zirconia		
	Electron Beam Melting (EBM)				
Vat Photopolymerization	Stereolithography (SLA)	Photopolymers Ceramics	Epoxies and acrylates, Alumina, Zirconia	High building speed Good resolution Over-curing scanned line shape High cost for supplies and materials	
Binder Jetting	Indirect Inkjet Printing (3DP)	Polymer powder Ceramics	Plaster Resin	Full-color object printing Wide material selection High porosities on finishing parts Require infiltration during post-processing	

Sheet Lamination	Laminated Object Manufacturing (LOM)	Thermoplastics polymers Wood Metals Ceramics	Polyamide, Acrylonitrile Butadiene Styrene, paper, metallic sheet, ceramic materials	High surface finish Low material, machine, and process cost De-cubing issues	

3. METHODOLOGY: USING 3D PRINTING IN SOIL SCIENCE

To investigate the state of the art of 3D printing use for soil science research purposes, a survey was conducted on Scopus, using the keywords "3D Printing", "Additive Manufacturing" and "soil" or “agriculture” for the title and the abstract. Indeed, for some applications of 3D printing in soil science concerning agriculture, the keyword “soil” does appear neither in the title nor in the abstract. The final search equation was:

TITLE-ABS ((((3d OR 3-d OR (three-dimensional)) PRE/0 print) OR (additive PRE/0 manufactur*)) AND (soil OR agricult* OR agro*))*

The selected sources (original articles, review and books) were analyzed with VOSviewer (https://www.vosviewer.com), a software tool for constructing and visualizing bibliometric networks. These networks can focus on journals, researchers, or individual publications, and can be built based on citation, bibliographic coupling, co-citation, as well as co-authorship relations. Moreover, this tool offers text mining functionality useful to construct and visualize co-occurrence networks of important terms extracted from a scientific literature body.

3.1. SELECTION AND CLASSIFICATION OF REFERENCES

The objective of the bibliometric search was to identify the scientific questions in which 3D printing is used in soil science. Further analysis of the references was thus conducted to check whether the 3D printing was used for scientific purposes specific to soil science or as a more generic tool, not dedicated to this scientific field, but only distantly related to soil. Each of the papers was thus screened to define if the 3D printing approach specifically helped to answer a scientific question linked to soil functioning or not. The references were then classified according to the soil functions that they addressed using six soil functions, as defined by Lal et al. 2018 (Lal et al., 2018).

1) Producing plant biomass, ensuring food, fodder, and renewable energy, which are the basis of human and animal life.
2) Cycling and storing water, nutrients, contaminants, and carbon.
3) Protecting and maintaining soil biodiversity, which is the largest reservoir of biodiversity on Earth.
4) Providing a basis for the development of technical infrastructures, such as houses, industrial environments, roads, and other facilities.
5) Providing sources of mineral raw materials, such as clay, sand, gravel, and others.
6) Supporting natural and cultural heritage and, as such, constitutes a historical memory of humans and its environment.

The first three ecological functions of soils are strongly related to the content and properties of soil organic matter (SOM), and its relationships with inorganic components. These three functions are strongly dependent on the chemical quality of the plant input and the functional diversity of the decomposer communities, which are strong drivers of the kinetics of plant litter (Dignac et al., 2017; Nguyen Tu et al., 2017; Schmidt et al., 2011). They are also strongly dependent on the stability of the organo-mineral associations and their spatial organization at the microscopic scale. The functions 4, 5, and 6 are technical, social, and economic functions, which are important for humans, and their managed and natural environments. They refer to a macroscopic consideration of soils. Soil functions 4 and 5 seal and/or excavate the soil, which loses their ecological properties defined as the functions 1, 2 and 3 (soil capacity for biomass production, filtering, cycling and maintenance of biodiversity).

4. RESULTS

4.1. OVERALL ANALYSIS

A total of 163 articles emerged from the literature survey conducted in July 2019 over the 2000–2019 publication period. These references were analyzed to create a bibliometric network based on author keywords, keeping only those that appeared at least twice, as it can be observed in Figure 1. A total of 36 keywords were considered. In this figure, the size of each circle representing a keyword is proportional to the number of articles in which the keyword appears. Additionally, the temporal evolution of the occurrence of keywords is represented by a color scale (from dark blue for 2000 to yellow for 2019).

Unsurprisingly, being a search keyword of the database search equation, “3D printing” and “Additive Manufacturing” appeared as the most cited keywords (32 and 3 occurrences, respectively). The next most-cited keywords are “agricultural machinery” (7 occurrences), “models” (5 occurrences), “design” (4 occurrences), “food” (3 occurrences), “processing” (3 occurrences) and “rapid prototyping” (3 occurrences). This means that in the past twenty years agricultural machinery was the most frequent application of 3D printing in the domains explored by our bibliometric equation. The circles’ color shows that the initial predominance (in the 2010s) of applications of 3D printing technologies for the manufacture of agricultural equipment has recently shifted to research topics such as biopolymers, biodegradation (of printed materials) and microfluidics (i.e. fluid circulation in the soil matrix at the microscale).

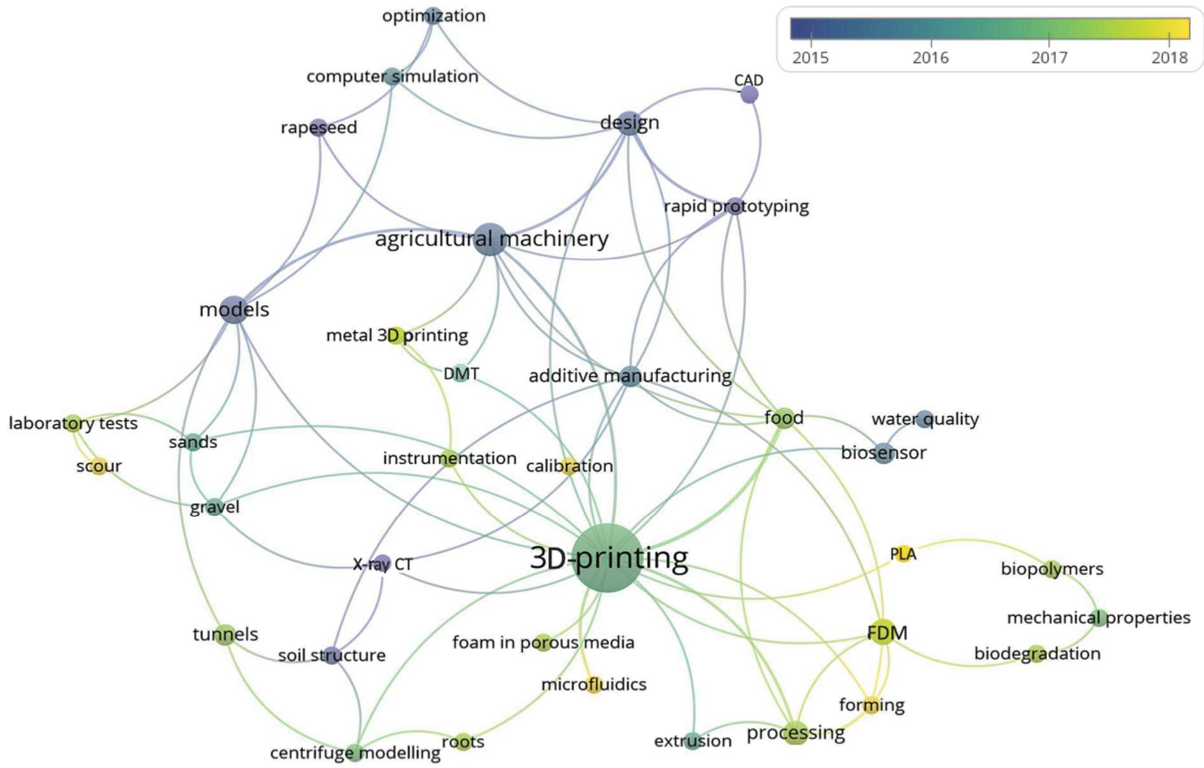


Figure 1. Visualization of keywords by average publication year. The size of each circle is proportional to the number of articles in which the keyword appears, and the color of the circle refers to the average year of publication (from purple for 2015 to yellow for 2018). CAD: Computer Aided Design; FDM: Fused Deposition Modeling; PLA: Polylactic acid; X-ray CT: X-ray computed tomography; DMT: Direct Metal Tooling

4.2. ANALYSIS OF A SELECTION OF ARTICLES ADDRESSING SPECIFIC SOIL FUNCTIONS

Since soil functions are relevant entries for interdisciplinary studies on ecosystem services (Keesstra et al., 2016), each article was associated with the soil function it addresses. The articles that did not relate to any soil function were discarded. In the end, we identified 41 articles, which are related to one or more soil functions. The selected articles are presented in Table 2, showing the 3D printing technologies and materials they implement (as described in Table 1) and the soil function they address.

It is important to note that some of the articles (5%) did not or only partially describe the implemented 3D printing method (technology and material), showing that the researchers used the printers and the materials available in their laboratories without analyzing or identifying the most appropriate 3D printing method for their purposes.

Table 2. Bibliometric survey selection of 41 articles that address a soil function. The articles are classified in alphabetical order by the first author and associated with the 3D printing technology and material they use, as well as the concerned soil function (1: biomass production, 2: cycling water and nutrients, 3: biodiversity, 4: basis for infrastructure, 5: source of raw material, and 6: natural and cultural heritage).

Authors	3D printing technology	Materials[1]	Soil functions
Bacher et al. (2015)	SLS PolyJet (MJM) FDM SLA	Alumide (M) and Polyamide (P) Resin (P) Acrylonitrile Butadiene Styrene (P) Prime Gray resin (P)	2
Bagrov et al. (2017)	SLS	Silica glass nanopowder (S)	5
Borecki et al. (2016)	FDM	Not mentioned (N)	2
Ceccanti et al. (2010)	Binder Jetting (3DP)	Glass-rich basaltic ashes (S)	5
Cesaretti et al. (2014)	Binder Jetting (3DP)	Metallic oxide (M)	5
Chang et al. (2016)	FDM	Acrylonitrile Butadiene Styrene (P)	1
Chow et al. (2017)	SLS	Martian soil simulant (O)	5
Cocovi-Solberg et al. (2019)	SLA	Photopolymer clear resin (P)	2
Dal Ferro and Morari (2015)	MJM	Visijet Crystal EX 200 (P)	2
Farooqui and Kishk (2018)	FDM	Acrylonitrile Butadiene Styrene (P)	2
Gao et al. (2018)	FDM	Acrylonitrile Butadiene Styrene (P)	1
Hanaor et al. (2015)	MJM	Fullcure 720 resin (P)	4
Iubin and Zakrevskaya (2018)	Not specified	Not mentioned (N)	5
Li et al. (2016)	FDM	Acrylonitrile Butadiene Styrene (P) PLA (P)	2
Liang et al. (2018, 2017, 2014)	FDM	Acrylonitrile Butadiene Styrene (P)	4
Lim and Chan, 2017)	FDM	Acrylonitrile Butadiene Styrene (P)	4
Mahabadi et al., 2018)	FDM	Acrylonitrile Butadiene Styrene (P) PLA (P)	2

Matsumura et al., 2017)	MJM	Cured resin (P)	4
Meijer et al. (2018)	FDM	Acrylonitrile Butadiene Styrene (P)	4
Mishra et al. (2018)	MJM	Resin Fullcure 720 (P)	4
Mondini et al. (2008)	MJM	Plastic (P)	4
Osei-Bonsu et al. (2018, 2017)	Polyjet (MJM)	Liquid resin (P) Acrylic-based material (P)	2
Otten et al. (2012)	SLS	Nylon 12 powder (P)	1,2,3
Ozelim and Cavalcante (2019)	SLS	Polyamide (P)	2
Pua et al. (2018)	Binder jetting (3DP)	Kaolin & Bentonite (S)	4,5
Rangel et al. (2013)	FDM	Plastic (P)	1
Ritter et al. (2016; 2017a,b; 2018a,b)	Polyjet (MJM)	3DP material (P) Visijet PXL powder & binder (P)	4
Shen et al. (2017, 2016)	Binder jetting (3DP)	Stainless steel and bronze (M) Not mentioned (N)	4
Su et al. (2017)	SLA	Formlabs Clear Resin (P)	4
Suescun-Florez et al. (2013)	FDM	Plastic (P)	2,4
Sylvain et al. (2016)	FDM	Plastic (P)	4
Tiausas et al. (2017)	Not specified	Not mentioned (N)	1,2
Zhang (2018)	FDM	Acrylonitrile Butadiene Styrene (P)	4

1 The material classification is Plastics (P), Metal-based (M), silicon-based (S), others (O) and not mentioned (N), according to the information provided by the paper authors

Among 3D printing technologies, Fused Deposition Modeling and Polyjet/Inkjet Printing are the most commonly used technologies in the soil science domain, accounting for about two-thirds of the articles, as shown in Figure 2. In terms of materials (Figure 3), plastics are the most commonly used (77%), maybe because these types of materials are used to develop the most well-known 3D printing technologies (FDM, SLA, and MJM). To the best of our knowledge, there is no utilization of biobased materials for applications dedicated to the investigation of soil functions.

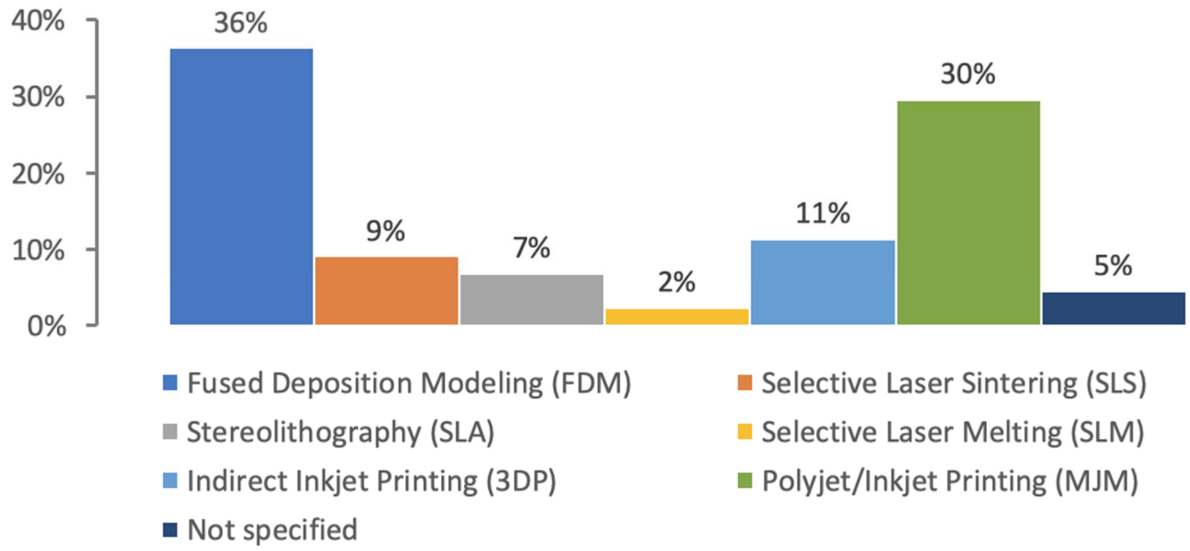


Figure 2. 3D printing technology used in the 41 selected articles related to soil functions.

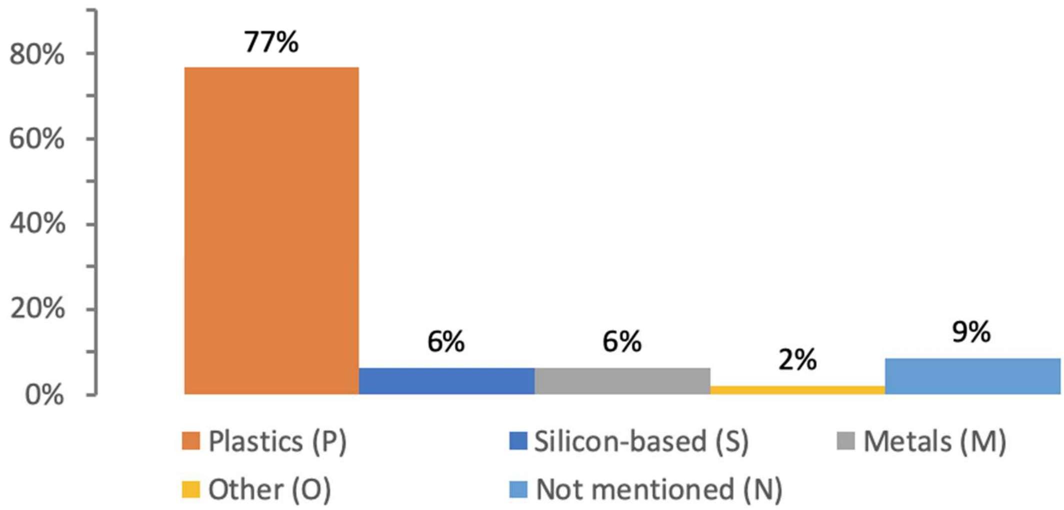


Figure 3. Materials used in the 41 selected articles related to soil functions.

In Figure 4, the 41 selected articles were further analyzed and classified according to the soil function they address. Most of the articles could be related to function 4 (soils as a basis for infrastructure) or 2 (soils for cycling and storing water, nutrients, and carbon), accounting for 46 and 28% of the articles, respectively. Nevertheless, the articles were not investigating element cycling itself but addressed methodological issues that must first be resolved. Function 5, for which soil is considered as a source of mineral raw materials, such as clay, sand, and gravel, is the subject of 13% of the articles, while functions 1 (production of biomass) and 3 (soil biodiversity) are addressed in only 11 and 2% of the articles, respectively. None of the selected articles was related to function 6 (natural and cultural heritage).

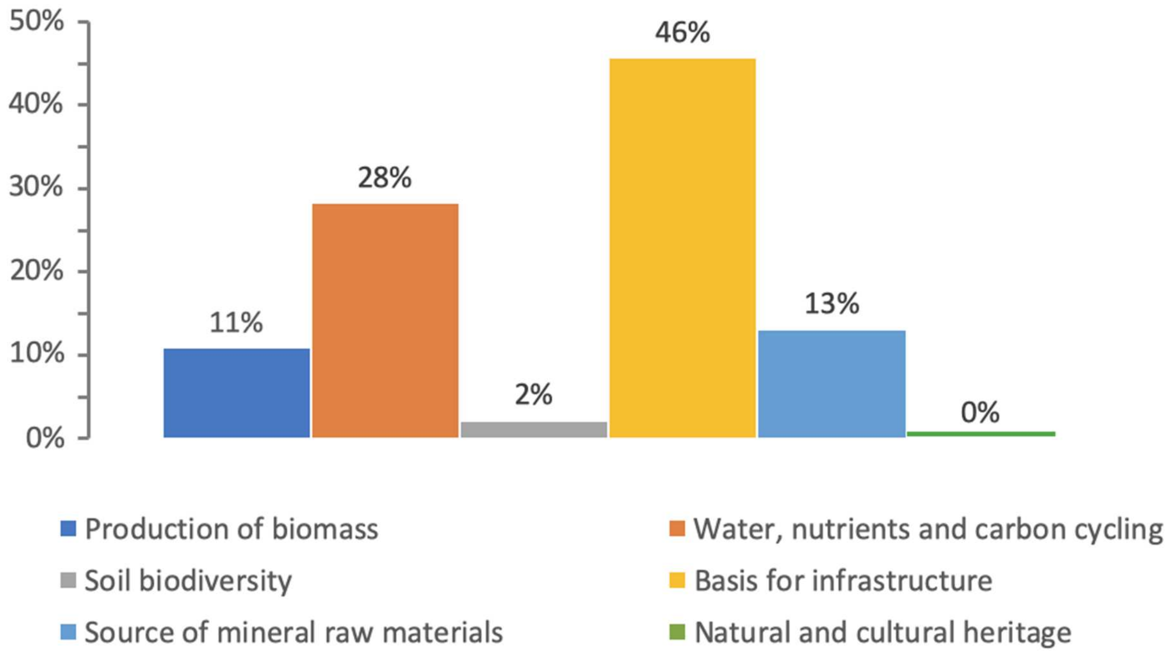


Figure 4. Soil functions addressed in the 41 selected articles related to soil science.

Some of the 41 articles made use of 3D printing for manufacturing equipment and devices used in soil-related activities (related to soil functions 1, 2, and 4). 3D printing appears in these articles as a flexible and easy-to-use prototyping technique for custom manufacturing of agricultural equipment (related to soil function 1 of biomass production). In this field, 3D printing allows adapting the tools to particular land or crop situations, as reviewed by (Javaid and Haleem, 2019) or to design innovative biomimetic tools such as the corn stubble harvester imitating the morphology of the nymph fore claws proposed by (Chang et al., 2016).

3D printing is also used in the field of soil science to build sensors for the study of soil properties, generally concerning the second soil function (element cycling). In many situations, 3D printing is presented as the simplest and cheapest, if not the only, way to obtain an object to be used in the construction of the desired device, in preference to the more expensive and complex conventional tool-machinery (Rangel et al., 2013). Such 3D-printed devices are, for example, an instrumented dilatometer for measuring soil disturbance during penetration (Shen et al., 2017, 2016), a permeameter (Rangel et al., 2013), or various housings for sensors monitoring soil properties (Borecki et al., 2016; Cocovi-Solberg et al., 2019; Farooqui and Kishk, 2018; Li et al., 2016; Sylvain et al., 2016; Tiausas et al., 2017). 3D printing is also used for prototyping innovative biomimetic probes, such as those imitating root growth. These probes, which imitate the root morphology, can move in the soil with a high penetration efficiency and a limited energy consumption typical of growing roots (Mishra et al., 2018; Mondini et al., 2008).

In the field of civil engineering and architecture (function 4), 3D printing is increasingly used to rapidly produce two types of customizable objects: either small-scale building models used to test building resistance to soil perturbations or objects devoted to soil stabilization. In the first group of studies, small scale houses are produced with 3D printing and placed on the soil to evaluate house stability, depending on their characteristics (i.e. position, length, and facade openings). Different constraints that affect building stability can be tested, such as soil tunneling below 3D printed buildings (Ritter et al., 2016; Ritter et al., 2017a,b; Ritter et al., 2018a,b), or water erosion (Suescun-Florez et al., 2013). The second group of geomechanical applications consists of building 3D-printed objects dedicated to the improvement of soil mechanical properties (Lim and Chan, 2017). For example, the stability of a vegetated slope was investigated by equipping a soil profile with a model plant root system produced with plastic material (ABS, Acrylonitrile Butadiene Styrene) and submitting it to mechanical tests (Liang et al., 2018, 2017; Meijer et al., 2018).

Soils have also been used as a cheap, easily available, and sustainable source of raw material for 3D printing in alternative to fossil resources (Iubin and Zakrevskaya, 2018). Printing with soil was mostly achieved with the binder jetting technology in applications related to architecture and art. It was combined with binding agents to enhance the chemical and structural properties of the printed structure (Mitterberger and Derme, 2019; Derme and Mitterberger, 2020). None of these applications required replication of soil characteristics. Furthermore, one of the disadvantages of using soil as a material is its heterogeneity and the resulting lack of control over the composition of the printed object. 3D printing has also been successfully tested with exotic materials such as Moon or Mars regoliths, to prepare habitat building in the event of establishment outside the Earth, using 3D printing technologies adapted to the specific conditions in outer space (Bagrov et al., 2017; Ceccanti et al., 2010; Cesaretti et al., 2014; Chow et al., 2017).

Finally, a group of articles is dedicated to the printing of soil models, reproducing physical, chemical, and biological behavior and soil evolution dynamics. This topic raises many opportunities and challenges for research in soil science that are discussed in the following section.

5. DISCUSSION: OPPORTUNITIES AND CHALLENGES OF 3D PRINTING IN SOIL SCIENCE

5.1. PRINTING TECHNOLOGIES TO PRODUCE PHYSICAL ANALOGS OF SOIL (RELATED TO SOIL FUNCTIONS 5, 2 AND 3)

3D printing is increasingly used to produce analogs of granular soil particles or soil profile for geotechnical tests, as an alternative to numerical simulations or laboratory (Hanaor et al., 2015; Matsumura et al., 2017; Su et al., 2017). Numerical simulations are indeed prohibitively expensive or are carried out with highly simplified particle shapes without a real understanding of the reliability of the simulation being achieved. On the other side, geotechnical laboratory tests are limited due to the unavoidable structural variation in the granular assemblages of the specimens. By contrast, 3D printers using resin polymers can generate individual particles of repeatable shapes or assemblages of bonded particles whose particle shapes, sizes, and arrangements match those of natural samples. Besides, the construction of 3D-printed objects is less time-consuming than that of numerical or hand-made models. However, the representativeness of their mechanical response has still to be tested and compared to the results of numerical or geotechnical simulations. In particular, current investigations are focused on the influence of both materials (powder, adhesive, binding agents) and technology on the micro- and macro scale mechanical behavior of the 3D printed specimens (Matsumura et al., 2017; Su et al., 2017).

3D printing also offers a great potential for investigating how the 3D pore arrangement regulates fluid circulation and biological activity in soil (e.g. root or fungal mycelium growth, movements of microbes, or soluble substances), properties respectively related to soil functions 2 and 3. The main challenge of 3D printing techniques for the construction of soil models is their ability to print objects exhibiting a customized 3D-arrangement of the pore system or to reproduce the physical properties of soil at an adequate resolution. 3D printers using Selective Laser Sintering (SLS) technology (Table 1) can reproduce the imaged porosity and the macro-pore shapes corresponding to the resolution of X-ray computed tomography images (Dal Ferro and Morari, 2015; Bacher et al., 2015). Investigations are conducted to test how various properties of the printed porous media impact fluid motion (Osei-Bonsu et al., 2018, 2017). The major caution point for SLS printing of soil analogs is the incomplete removal of powder residues that may remain inside the printed object despite the immersion of the sample in acetone (Ozelim and Cavalcante, 2019). Pore clogging indeed would decrease the resulting porosity and limit pore connectivity, affecting fluid flow (Dal Ferro and Morari, 2015). Pore clogging due to residual powder can be avoided by using a liquid printing material as in stereolithography (Bacher et al., 2015). A second critical challenge for investigation of soil functions 2 and 3 with 3D-printed soil models is the limitation of most 3D printing technologies in terms of the minimum wall thickness, minimum buildable details, and maximum dimensions of the model (Ozelim and Cavalcante, 2019). These limitations have direct impacts on the accuracy of the reproduced microporosity (arrangement of pores at the micromillimeter scale), which strongly controls elements cycling. Current 3D printing technologies can only control pore diameter down to 60 micrometers (Kadkhoda-Ahmadi et al., 2019). Smaller pores occur but are not intentional: they are those imposed by the selected 3D printing method.

Research efforts are also focused on finding the 3D printing method, i.e. the combination of material and technology, which could reproduce the hydraulic properties and wettability of soil. On the material side, hydrophobicity must be carefully considered. (Mahabadi et al., 2018) dismissed stereolithography technology because corresponding materials were too hydrophobic for reproducing soil hydrological properties. By contrast, Bacher et al. (2015) showed that stereolithography with Prime Gray, a plastic material, provided a good accuracy and an unclogged macropore system with a relatively high hydrophobicity (contact angle 65°). Fused Filament Modeling (FDM) technique with Nylon, a plastic with a low hydrophobicity (contact angle 40°), also allowed modeling the wetting behavior and hydraulic conductivity of a natural soil sample (Mahabadi et al., 2018).

In alternative to studies optimizing the technology and materials to produce soil physical analogs, demonstrated the ability of the 3D printing technology based on material extrusion to print real soil material, without additives or expensive energy sources (Pua et al., 2018). Also, they successfully built composite objects reproducing soil three-dimensional heterogeneity using several contrasted soil materials. Their technical device must still be improved, as voids were observed at the interface between two types of soil materials, possibly by subjecting the printed object to vacuum.

5.2. PRINTING SOIL AS A SUPPORT FOR LIFE: BIOCOMPATIBILITY (RELATED TO SOIL FUNCTIONS 1, 2 AND 3)

The pore connectivity and the porosity of 3D printed soil models discussed above govern the specific interactions between different living organisms, between organisms and their resources. Another essential property of the soil analog for modeling of soil functions 1, 2, and 3 is its biocompatibility. Biocompatibility first implies that the printed material should not be toxic for living organisms (plant seeds and roots; macro, mesofauna, or microorganisms). Besides, 3D-printed objects used as physical habitat should deliver living resources (water, organic matter, nutrients) to guarantee organism viability and growth. The plastic materials commonly available for 3D printing technologies do not meet these requirements. Often toxic, they are hydrophobic and water repellent, which is prohibitive for supporting life.

Various biocompatible polymers have recently received tremendous attention as promising alternative bioinks for 3D printing technologies. For example, pectin, a heterogeneous polysaccharide present in the plant cells, has been recently reported as a suitable hydrocolloid used to develop new materials for tissue engineering (Cernencu et al., 2019), and food applications (Vancauwenberghe et al., 2018). Alginate biopolymers are also of high interest because they can entrap water and their chemical structure can be modified and implemented with specific nutrients (Gopinathan and Noh, 2018; Liu et al., 2019). Biopolymers, such as bovine serum albumin (BSA) or gelatine are also being used in particular for lab-on-a-chip applications (Aleklett et al., 2018). In lab-on-chip applications, the desired pattern of the chip is sometimes obtained with synthetic biocompatible polymers, for example, a PDMS silicone exposed to UV light (Aleklett et al., 2018). Some biopolymers, such as BSA, can also be directly cross-linked with pulsed laser light into a biocompatible hydrogel exhibiting the desired shape (Connell et al., 2012, 2010). They can be mixed with gelatine and specific bacterial communities before chemical cross-linking with pulsed laser light with a photosensitizing molecule (methylene blue or Rose Bengal) (Connell et al., 2013). Some applications interestingly use transparent materials enabling visual and spectroscopic control of soil functioning (Downie et al., 2012). Even if they physically reproduce soil pore geometry and properties at fine scales (Aleklett et al., 2018), lab-on-a-chip systems cannot be considered as replication of soils, since they do not reproduce the spatial arrangement of these microscopic habitats. However, they could inspire soil science developments in terms of biocompatible materials.

To improve the spatial representation of the complex soil system, the 3D printing process should also allow the addition at precise locations of specific components, such as nutrients enriched biopolymers or viable organisms, as it was successfully achieved by several (Ringeisen et al., 2015; Taidi et al., 2016).

5.3. PRINTING A SOIL THAT RESPECTS THE DYNAMICS OF SOIL PROPERTIES (RELATED TO SOIL FUNCTIONS 1, 2, 3 AND 5)

Soil is a living system. Its physicochemical properties are constantly evolving under the action of biotic agents (microbes, micro, and mesofauna, plant roots, etc.), related to soil biodiversity or of abiotic processes (solubilization, redox reactions, adsorption, compaction, freezing, etc.) related to pedo-climatic conditions. The use of multi-material printing, mainly using MJM, and also bio-printing technologies (Lopes et al., 2018), allows the development of shape-morphing objects that respond to external changes, such as humidity, light or touch (Sydney Gladman et al., 2016). This so-called 4D printing technology uses self-assembly programmable materials to build objects that are no longer simply static and dead but rather transformable (Pua et al., 2018). This technology has already been applied in tissue engineering, biomedical devices, and soft robotics (Velasco-Hogan et al., 2018). Such approaches are promising for reaching a better representation of the complex and dynamic soil matrix.

On the other side, to be used in soil science experiments with living organisms, 3D-printed objects should not exhibit artefactual dynamics. They must have the ability to self-retain their 3D printed macro and micro-structure, as real soil does when subjected to physical and chemical constraints favorable to organism growth or generated by the organism activity. For example, it may be necessary to autoclave the object at high pressure to optimize the growth of specific microorganisms and prevent the development of competing bacteria or fungi. During plant growth or incubation experiments using the printed object, water may circulate in the object pores. Root and microorganism's activity may generate protons and acidify material surfaces. For example, the printed soil block must be resistant to biotic stress due to fungal growth, as shown by Otten et al. (2012) To meet these requirements, the materials or combination of materials used to produce the object shall have a wide range of thermal compatibility, sufficient rigidity to prevent collapse due to physical disturbances (e.g. through high cross-linking capacity) and surfaces with buffering properties.

6. CONCLUSIONS

The present article evidences that 3D printing has emerged as a revolutionary technology, promising to push the boundaries of experimental research. It advantageously allows the fast and inexpensive production of endlessly replicable identical and customizable objects, for conducting experiments. Soil science, like many other fields, has already started to explore the research opportunities opened up by various 3D printing technologies. Most of the applications appearing in our bibliometric survey concern soil functions 4, and 5, in which the soil is considered either as a source of raw materials or as the basis for the development of technical infrastructures. These applications refer to the fields of civil engineering or architecture more than soil science since they do not take into account the functioning of the soil itself but simply consider soil either as a source of raw materials or as the basis for the development of technical infrastructures.

The use of 3D printing in soil science, for research issues related to carbon and nutrient cycling and storage (function 2), which impact biomass production (function 1) and biodiversity (function 3) is a new research opportunity. The under-representation of applications addressing these functions in the bibliometric survey may be explained in the first place by the limited user group that is currently involved in the development and use of 3D printing in soil science. The emphasis on the potentialities of this technique that we provide in this article will hopefully enlarge this potential user group. It can be particularly attractive for researchers developing participatory research projects by producing identical, reproducible samples with strict and controlled composition and structure or for those looking for tools and indicators to provide stakeholders with an assessment of soil health and/or ecosystem services.

If the deployment od 3D-printing in soil science is still limited, it is also because of the technical limitations that we analysed here. One of the main limitations is the difficulty of adequately representing the soil porous network with 3D printing. Indeed, soil functioning is strongly related to the spatial arrangement of soil pores and of soil constituents, the accessibility of resources, and the circulation or growth of living organisms in the soil pore network. In addition to the classical criteria of cost and availability of 3D-printing material and process, we have identified three specific constraints that need to be considered and improved to use 3D printing to build realistic soil models for use in soil science: (i) finding suitable biocompatible material (depending on the scientific question, any natural biomaterials, especially those derived from plants, could be of interest), (ii) choosing a 3D printing technology whose spatial resolution is adapted to the experiment it is dedicated (down to the submicrometric scale) and (iii) implementing the 3D printing method that produces chemically and mechanically stable objects, when brought into contact with living organisms.

We are confident that all technical limitations will be overcome in the next years through enhanced dialogue between disciplines and in-depth scientific reflection on the objectives and outputs of the applications. Soil scientists have to precisely define the technical specifications related to their study and work closely with 3D printing developers to meet them. To meet the specifications of soil scientists, 3D printing developers may recommend the use of materials and techniques already available or must implement new research programs. This dialogue will contribute significantly to the progress of 3D printing technologies and materials and will also benefit other application areas of 3D printing, such as food processing or the agriculture of the future on Earth but also on the Moon or Mars in the context of the conquest of space.

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