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MACHINE USE AND DIGITALIZATION IN EARTH BUILDING PRODUCTION

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ABSTRACT
Earth is a building material that can be reused with innovative design Technologies in the field of architecture, due to its advantages such as being recyclable, cost-effective, having low carbon emissions, and requiring very little energy use inthe process of building production. Among these innovative applications, the use of earth through prefabricated element production, mechanisation, 3D printers and robotic spraying tools, enables it to take part in the transformation in the digital production process. The primary research topic in this study is to identify the potential effects of contemporary construction technologies on the creation of earthen structures, as well as the degree of advancement they can provide progress. Within the scope of the research problem, it is aimed to examine the examples of earthen structures produced with contemporary building technologies and the studies in the literature through bibliometric data analysis. The method followed in the study; firstly, in order to determine the number of studies in the literature, important authors and sources, sample data of the studies with the keywords "earth building", "rammed earth", "adobe", "3d printer", "digital production" and "additive manufacturing" were taken in the "Web of Science" database and bibliometric data analysis was created through the "VOSwiever" programme. Furthermore, scientific studies and building examples within the scope of the subject in "Sciencedirect", "Google Scholar", "Taylor & Francis Journal", "International Thesis Centre" and "Web sites" databases were examined and a conceptual framework was created. According to the findings obtained; it was determined that the most studies in the last ten years belonged to 2012 and the countries of America, France, England and Spain were frequently mentioned in the subject. In the conclusion of the study evaluates the potential effects, current situation and difficulties of technological developments in the production process of earthen struare evaluated. According to the findings obtained; it was determined that the most studies in the last ten years belonged to 2012 and the countries of America, France, England and Spain were frequently mentioned in the subject. In the conclusion part of the study, the potential effects, current situation and difficulties of the technological developments developed in earthen structures in the production process are evaluated..

Keywords: *Earth building, Earth building techniques, Fabrication, 3d printers, Digital manufacturing.*

TOPRAK YAPI ÜRETİMİNDE MAKİNE KULLANIMI VE DİJİTALLEŞME

ÖZET
Toprak, geri dönüştürülebilir ve ekonomik olması, düşük karbon salınımına sahip olması ve yapı üretim sürecinde oldukça az miktarda enerji kullanımı gerektirmesi gibi avantajlarından dolayı mimarlık alanında yenilikçi teknolojiler ile yeniden kullanılabilen bir yapı malzemesidir. Yapılan bu yenilikçi uygulamalar; toprağın, günümüzde, prefabrike eleman üretimi, mekanizasyonu, 3d yazıcı ve robotik püskürtme araçları aracılığıyla kullanılması, dijital üretim sürecindeki dönüşümünde yer almasını sağlamaktadır. Bu çalışmada

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çağdaş yapı teknolojilerinin, toprak yapıların üretimindeki potansiyel etkilerinin neler olduğu ve ne düzeyde ilerlemeler sağlayabildiği temel araştırma problemi olarak belirlenmiştir. Araştırma problemi kapsamında çağdaş yapı teknolojileriyle üretilmiş toprak yapı örnekleri ve literatürde yer alan çalışmaların bibliyometrik veri analizi aracılığıyla incelenmesi amaçlanmıştır. Çalışmada izlenen yöntem; ilk olarak literatürde yer alan çalışmaların sayısını, önemli yazarları ve kaynakları tespit etmek için "Web of Science" veritabanında "toprak yapı", "sıkıştırılmış toprak", "kerpiç", "3d yazıcı", "dijital üretim" ve "eklemeli üretim" anahtar kelimeleri ile çalışmaların örnek verileri alınmış ve "VOSwiever" programı aracılığıyla bibliyometrik veri analizi oluşturulmuştur. Ayrıca "Sciencedirect", "Google Scholar", "Taylor & Francis Journal", "Uluslararası Tez Merkezi" ve "Web sayfaları" veritabanlarında konu kapsamındaki bilimsel çalışmalar ve yapı örnekleri incelenmiş ve kavramsal çerçeve oluşturulmuştur. Elde edilen bulgulara göre; son on yılda en fazla çalışmanın 2012 yılına ait olduğu ve konu dahilinde Amerika, Fransa, İngiltere ve İspanya ülkelerinin adının sıklıkla geçtiği saptanmıştır. Çalışmanın sonuç bölümünde ise toprak yapılarda geliştirilen teknolojik gelişmelerin üretim sürecindeki potansiyel etkileri, mevcut durumu ve zorlukları değerlendirilmiştir.

Anahtar Kelimeler: *Toprak yapı, Toprak yapı teknikleri, Fabrikasyon, 3d yazıcılar, Dijital üretim*.

1. INTRODUCTION

In recent years, the use of fossil fuels, high rates of urbanization activities and irregular land use have led to an increase in surface temperatures and climate change. According to studies, the construction sector is responsible for 40% of global energy consumption, 38% of greenhouse gas emissions, 12% of global drinking water use and 40% of solid waste generated in developed countries (Agusti-Juan and Habert, 2017:2780). Due to reasons such as environmental pollution and the climate crisis, in which the construction sector plays a major role, efforts are now being made in the field of architecture, to produce structures that will cause the least harm to nature. Therefore, today, earthen materials in traditional and local architecture are once again beingpreferred again (Erbil and Seçer, 2017:32). Earth has been one of the basic building materials used from the past to the present due to its easy accessibility and shaping and effortless production compared to other building materials such as stone and wood. Even today earthen buildings can meet the current needs of almost every segment of the society without causing environmental pollution and at the best level with minimum energy (Kafesçioğlu, 2017:140). Other interesting features of earthen buildings are that they provide thermal comfort, protect indoor humidity, resist fire and are physically and psychologically healthy thanks to their strong perception of place. In the past, earth architecture, a branch of traditional architecture, involved more than one technique in building production and the earth to be used could be supplied from the local region. However, this attitude does not mean that every type of earth can be used in building production. According to Çiçek (2014), construction earth is defined as: "*Cohesive earth consisting of gravel, sand, silt and clay, which can be used in the building as they are taken from nature or after a correction process is applied, and sandy, marly, pozzolanic soils that do not contain enough fine grains and do not have cohesion qualities, and all special quality earths encountered in some regions are defined as "Building earth"* " (Çiçek, 2014).

According to Hamaard et al. (2016), earth construction techniques are classified into two different types: wet and dry methods (Hamard et al., 2016:105). The wet method refers to the use of mouldable earth mixtures with relatively high moisture content through the technique of tempering and densifying the mechanical strength of the structure by tempering and densifying during the drying and shrinking process until the optimum moisture content is reached (Gomaa, 2022:2-3). Adobe block, cob and earth plaster can be classified as wet method, while rammed earth wall and rammed earth blocks can be classified as dry methods. Developing technologies of our age affect the field of architecture as well as many other disciplines and traditional construction methods have been integrated with contemporary building technologies in recent years. The computer-aided design and production of the model designed and produced in three dimensions, the integration of numerical information such as shape, material and size with CAD/CAM technology shape the production (Solmaz Şenel and Güller, 2017:140). Therefore, the digitalisation of an environmentally sensitive building material such as soil through innovative technologies such as CAD software, computer-aided design tools, artificial intelligence technologies and 3D printers enables modern and sustainable building production against the climate crisis of our age. In the era of modern technology, intensive research and applications on earthen buildings show that digital technologies and mechanisation are important to promote the reuse of earth against the climate crisis. Digitalisation allows the incorporation of computer-aided design tools and many similar sourcing from the procurement of materials to the building production process, enabling a smooth and quality work to be carried out. In this context, the use of earth-based building materials such as adobe and clay with 3d printing technologies is effective in increasing the productivity of earth buildings. The conducted research and practies support the recognition that the consideration of raw earth in 3D printing technologies can open up a range of active research areas, be it mechanical and physical properties, different design opportunities, local economy and skilled labour, or environmental and geological issues (Gomaa et al., 2019:230). Other important developments include the use of pneumatically assisted tools instead of wooden rammers in traditional compaction techniques as well as the production of compacted earth walls in the manufacturing process. Moreover, the production of earth walls in a factory environment establishes a connection between the machines and the project coordinators, ensuring that the technological tools in the design and construction process work in harmony. Today, many organisations and companies around the world, such as Rammed Earth Enterprise in Australia, Sirewall in the USA, Rammed Earth Artisan Ltd in Canada and Earth Structures Europe Ltd in the UK, are involved in earth construction under modern conditions (Gomaa et al., 2022:4). In general, conducting scientific studies to integrate a local material such as earth with digital technologies enables the construction of structures that can achieve better results in the design and production process of the material and offer new alternatives to environmentally harmful building materials such as concrete.

2. FABRICATION PROCESSES IN THE PRODUCTION OF EARTHEN BUILDING

In the production of earth blocks, the use of hand-made moulds in the past has recently been replaced by extruders. These extruded earth blocks, which are formed with the help of extruders, can be produced in a short time in a factory environment with perforated internal parts and make significant contributions to the production of earth buildings. Another example of mechanisation is the use of spraying tools in the formation of stabilised earth walls. These spraying tools are similar to the concrete puring technique and create the possibility of on-site production. In the case of rammed earth wall elements, systematic progress can be achieved by incorporating fabrication processes and an automated production industry is being developed.

2.1. Stabilised Extruded Earth Blocks (Green Brick)

The bricks formed by compressing the unfired earth in the factory using an extruder are called "green bricks" or stabilised extruded earth blocks (Figure 1). These bricks are generally the same size, homogeneous and smooth as fired bricks and this technique has been used in the brick industry for a long time (Nitelik Gelirli, 2022:55). It is important to protect these earth blocks from adverse climatic conditions in the field and during transport.

Figure 1. Stabilised Extruded Earth Blocks (Green Brick) (Url-1).

2.2. In-Situ Pouring Technique With Machine Assistance

It is a technique based on spraying the stabilised earth with a mixture of aggregate and water at high speed (Curto et al., 2020:2-3)(Figure 2). This technique can be used with double or single sided moulds. The earth mixture is filled by spraying from top to bottom in double-sided moulds and in the opposite direction in single-sided moulds (Nitelik Gelirli, 2022:57). After spraying, manual corrections can be achieved to obtain a smooth surface. In addition, different textures can be obtained by spraying soil plaster on reinforced concrete facades.

Figure 2. Spraying process in single-sided (left) and double-sided (right) moulds (Curto et al., 2020:3).

2.3. Manufactured Rammed Earth Walls

Another technique used in earth structures depending on on-site production is rammed earth walls. Earth walls produced with this compaction technique are obtained by compressing the mixture of water and dry earth in layers in double-sided moulds using wooden mallets or pneumatic compaction tools (Figure 3). The need for removable moulds in the design of rammed earth walls, limits the design and shaping of these walls (Erbil, 2018:19). However, the customisation of advanced formwork systems can enable the production of structures with curvilinear shapes instead of sharp corner points (Figure 4). Nowadays, improved formwork systems and electric or pneumatic compaction devices are important in reducing labour requirements and have made rammed earth techniques feasible in some industrialised countries (Minke, 2006:52).

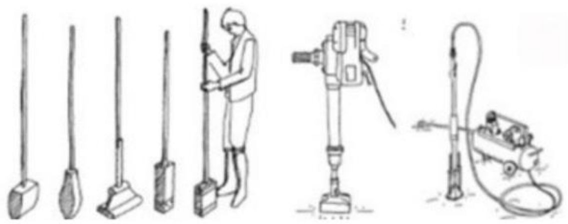

Figure 3. Conventional (left) and improved (right) compaction tools (Minke, 2006:54).

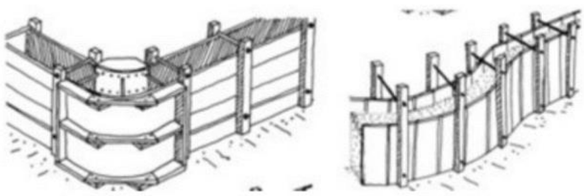

Figure 4. Customised mould systems (Minke, 2006:53).

In cases where no additives are added to the rammed earth mixtures, it can be returned to its original form by adding sufficient amount of water to the material during the demolition process of the building. This allows the recycling of rammed earth walls after they have served their purpose without any loss of quality in the material. Since earth is a fireresistant material, rammed earth walls can be used to create fire resistant structures.

With the development of the building industry in recent years, the compaction process can be fabricated to produce more homogeneous and stable rammed earth walls. Prefabricated rammed earth wall elements are produced in 50-80 m long and 1.3 m high moulds and stored in a warehouse to ensure that the material is formed independently of the site work programme or climatic conditions (Heringer et al., 2019:50-51). The Austrian company Lehm Ton Erde LLC, headed by Martin Rauch, is one of the renowned companies in the production of rammed earth buildings with intensive and developed techniques in prefabrication (Figure 5). Prefabrication has many advantages over on-site production, such as independence from weather conditions, accurate costing and reduction of on-site construction time(Rauch, 2020:7). In addition to this, fully automated production is being sought by integrating robotic arms and 3D printers into the fabrication processes. The Australian company Form Earth© is developing automatic compaction earth machines with automatic sliding mould systems called Freeform (Figure 6).

Figure 5. Lehm Ton Erde LLC Company in Austria Prefabricated Manufactured Rammed Earth Wall Practices (Rauch, 2020:2)

Figure 6. Sliding Mould System of Form Earth© Company in Australia (Url-2).

2.4. Prefabricated Manufactured Rammed Earth Walls

2.4.1. Druckerei Gugler

Located in Austria, this building was designed by Herbert Ablinger, Vedral & Partners and functions as a printing house. The walls of this 3-storey building are made of rammed earth technique. The walls of this building, designed by Martin Rauch, are made using the Pise technique and continue along the length of the building, providing an optimal indoor atmosphere and warmth (Url-3)(Figure 7).

(a) (b)

Figure 7. Images of the building (a),(b) (Url-3)

2.4.2. Alnatura Campus

The Alnatura Campus in Germany by the organic supermarket chain Alnatura is a commercial service building with conference facilities and a restaurant. The integrated core insulation and geothermal heating systems, as well asthe use of industrial production methods to prefabricate rammed earth wall elements are the highlights of the project, creating one of the largest earth-faced buildings in Europe (Url-4) (Figure 8). The building was also awarded with the 2019 German Sustainability Architecture Prize.

Figure 8. Image of the building (Url-4).

2.4.3. Ricola Kräuterzentrum

This building in Switzerland, this building was designed by Herzog & de Meuron. Designed as a factory and warehouse, it is over 100 metres long, 11 metres high and almost 30 metres wide (Url-5). Its purposeis to clean, dry, process and store the surrounding plants. The facade of the plant centre is made of prefabricated earthen building elements. The mix used in the facades is derived from clay extracted from the site and nearby quarries. To produce the soil mix, clay, marl and excavated material were mixed, compacted in a mould and finally the layers were laid in blocks (Url-6) (Figure 9).

Figure 9. Image of the building (Url-6).

2.4.4. L' Orangerie

This is an office building in Lyon, France, designed by Diener & Diener (DK) Architects and Clement Vergely Architects (FR). The office building, in which 286 prefabricated and unstabilised earth blocks are used in the construction of arches to form the load-bearing system on the façade, and timber is used for horizontal structural elements such as beams and floors, stands out as one of the important buildings recalling the rammed earth building tradition (Pedergnana, 2023) (Figure 10). The arched design of the rammed earth blocks in the building provided the opportunity to receive more sunlight on the façade formed by the windows. This opportunity extends the plan between the street and the landscaped courtyard and enhances the aesthetic appearance of the façade.

Figure 10. Image of the building (Pedergnana, 2023).

2.5. Additive Manufacturing Technique By 3d Printing Systems

According to Özgel Felek (2019), 3D printing technology, which is frequently used in additive manufacturing technology, is a process in which a three-dimensional object modelled in a computer-assisted environment is divided into layers and the material mixed in each layer is poured and overlapped (Özgel Felek, 2019:290). In recent years, 3D printing systems have been used in the field of architecture, which forms the basis of additive manufacturing. 3D printing technology has many advantages such as reducing the cost, time and margin of error in the building production process; as well as reducing environmental damageby preventing waste. Additive manufacturing using 3D printers contributes significantly to the automation of the construction process starting from the computer-aided design models based on mixing ratios and types of building materials. The fact that this developed technology has a positive impact onsustainability leads to the use of local materials other than concrete. For example, sustainable structures of various shapes are being created by using earth-based building materials such as adobe and clay in 3D printing systems. However, the behaviour of the newly mixed earth-based material planned to be printed should be well adapted to each step, and then it is important to find a mixture design perspective between the form stability and durability of the layers deposited to be fluid for pumping and extrusion (Perrot et al., 2018:673).

2.6. Earth Building Examples Produced Digitally with 3d Printig System

2.6.1. L' Gaia House

The Gaia House project is an eco-sustainable earth house model produced by WASP in Italy. It is designed to combine exterior walls, natural ventilation system and thermal-acoustic insulation system, 3D printed on site by WASP, into a single solution (Chiusoli, 2018)(Figure 11). Raw earth, straw and rice husks were used in the mixt to create the exterior walls. The binder agents used in the mix give the structure both durability and different geometric properties. Complex geometries of traditional materials can be realised with the multiple benefits of a cost-effective design.

Figure 11. Images of the building (Chiusoli, 2018).

2.6.2. L' Gaia House Clay Rotunda

Located in Bern, Switzerland, the building was designed by research and architecture firm Gramazio Kohler. Built insideof the Gurten Brewery in the city of Bern, the cylindrical structure with soundproof clay-based exterior walls is one of the most important examples of 3D printing and cost-effective design. The structure is approximately 11 m in diameter and 5 m in height, and was built in situ by a robotic system that assambled more than 30,000 clay bricks over a period of 50 days (Url-7)(Figure 12). The Clay Rotunda project also combines the traditional knowledge of clay structures with contemporary technology and production by using a local material such as clay with a 3D printing system and robotic arms.

Figure 12. Images of the building (Url-7).

2.6.3. Tecla

Tecla, a combination of technology and clay, is a residential building in Italy, built by Mario Cucinella Architects in collaboration with 3D printing specialists Wasp. The material used in the project was obtained from clay found in the nearby riverbed. The structure consists of 350 3D printed layers of clay and two connected dome-shaped volumes with a ribbed outer wall (Url-8) (Figure 13). This project is an eco-sustainable residential structure that can be rapidly and completely built using 3D printied earthen materials. At the same time, the structure can also serve as an example of how mass-produced housing structures that can be created for low-income communities and in emergency structures around the world.

Figure 13. Images of building (Url-8).

2.6.4. Terra Performa

In the project carried out by the Institute of Advanced Architecture of Catalonia, unfired clay is the basic building material. The project is an important research and application example of additive manufacturing structures in terms of combining three different 3D printing postures: robotic manufacturing, in-situ printing and printing with clay (IAAC, 2017) (Figure 14). The wall created in the project is completed with the modular combination of clay blocks produced by 3D printing.

Figure 14. Images of building (IAAC, 2017).

In the analyzed building examples, several research are carried out according to the novel ways created in the earth building. It was found that the scale of building created by modern compressed earth construction is not limited to residential units but can also be used in large-scale administrative buildings. Clay has been found to plays a crucial role in earth structures created using 3D printing technology, and that the components added to clay combinations may vary from Project to project. Clay, a soil-based substance, can now be designed in a more flexible way thanks to 3D printing technology. In addition, the robotic and computerised production processes carried out in a short time using 3D printing technology can provide significant benefits in the development of small-scale emergency shelter prototypes.This cutting-edge technology is paving the way for low-carbon, environmentally friendly, and eco-sustainable building development around the world. Table 1 summarizes the analyzed building examples under the headings of "material used", "structure name", "construction technique", and "country in which the structure is located".

Table 1. Examples of structures examined.

Material	Building Name	Building Technique	Country
Earth Mixture	Druckerei Gugler	Compressed with Pise Technique Earth Wall	Austria
Earth Mixture	Alnatura Campus	Prefabricated Manufactured Compacted Earth Wall	Germany
Earth Mixture	Ricola Kräuterzentrum	Prefabricated Manufactured Compacted Earth Wall	Switzerland
Earth Mixture	L' Orangerie	Prefabricated Manufactured Compacted Earth Wall	France
Raw Earth, Straw	Gaia House	Computational Manufacturing with 3d Printer	Italy
Clay	Clay Rotunda	Computational Manufacturing with 3d Printer	Switzerland
Clay	Tecla	Computational Manufacturing with 3d Printer	Italy
Clay	Terra Performa	Computational Manufacturing with 3d Printer	Spain

3. MATERIAL AND METHODS

In the context of modern earthen building production technologies, the number of studies carried out over time in the literature, as well as important authors, sources, and structure samples, are examined, and the potential impact of innovative construction technologies in earthen building discussed. The data for a number of studies were collected using the "Web of Science" database, and only the bibliometric data were analysed using the "Vosviewer" tool. In addition, resources such as "Sciencedirect," "Google Scholar," "International Thesis Center," "Taylor & Francis Journals," and "Web pages" were used to provide examples and conceptual frameworks.

Method of study; "earth building", "rammed earth", “adobe”, “3d printer”, “digital manufacturing” and “addictive manufacturing” from the database of "Web of Science"(WOS) to see the number of studies, current status, important authors and works made according to the years on the subject, reached a 12.889 number of keywords in data, building technology and architecture, filtered and data analysis of 1.281 studies was carried out via “WOS” and "VOSviewer" program. The limitation of the study is that the "Web of Science" database is compatible with the "VOSviewer" program and is easy to access. The distribution of the sample data according to the years, authors and research topics, co-authorship analysis, keyword analysis and country citation analysis were carried out. In addition, studies in the databases "Sciencedirect", "Google Scholar", "International Thesis Center", "Taylor & Francis Journals" and "Websites" were analyzed and a conceptual framework was established. As a result of the analyzes, the findings were revealed and the discussion and conclusion section and the study were completed. In addition, the research process carried out in the article is shown as schematically (Figure 15).

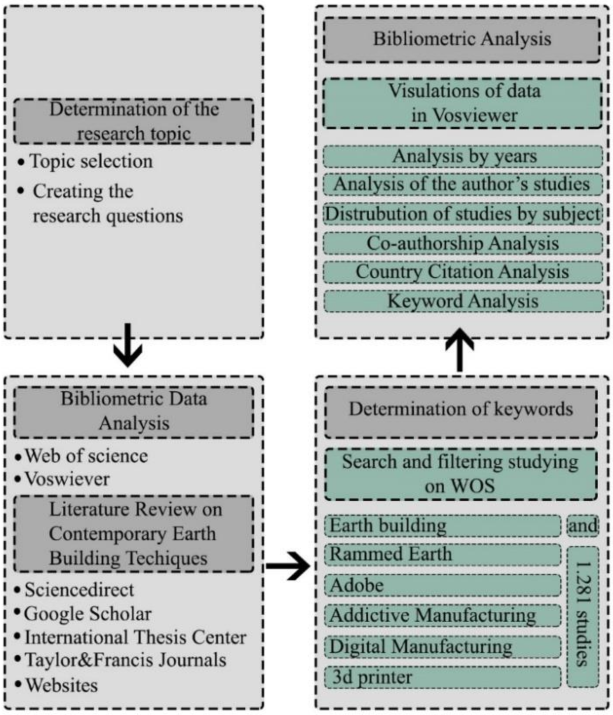

Figure 15. Research process.

4. FINDINGS AND DISCUSSION

This part of the study consists of the results obtained from the bibliometric analysis of the data using the "Web of Science" and "VOSviewer" programmes.

4.1. Alt Başlık Distribution of the Number of Studies by Year

Figure 16 shows the distribution of the 1.281 studies filtered through the "Web of Science" database according to the last 15 years.

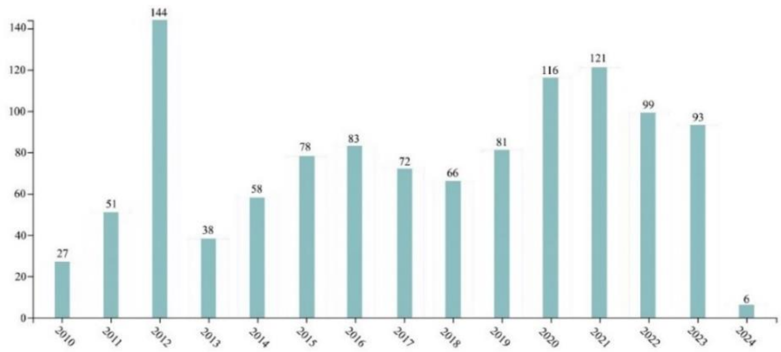

Figure 16. Distribution of 1.281 studies filtered by keywords in the "WOS" database according to years.

Analysing the distribution of 1281 studies according to the last 15 years, it was found that the highest number of records belonged to 2012 with 144 records and the lowest number of records belonged to 2024 with 6 records. However, it should be taken into consideration that the data obtained in the research to determine the lowest number of records is in the beginning period of 2024. On the other hand, the graph shows that the number of studies varies from year to year. Between 2010 and 2012, it is seen that the number of studies progressed with an increase. Between 2012 and 2020, there is a significant decrease in the number of studies, while it is understood that the studies in 2020 and later will approach the highest number in the graph. In this sense, it can be said that the studies on this topic will become mpre important in 2020 and beyond. It can be interpreted that the reason fort his situation are the natural disasters, epidemics and the climate crisis, which has been going on for many years but has clearly shown its effects in the last few years.

4.2. Distribution of Authors According to the Number of Studies

Figure 17 shows the distribution of the 1.281 data filtered through the "Web of Science" database according to the number of studies of the authors in the top 15.

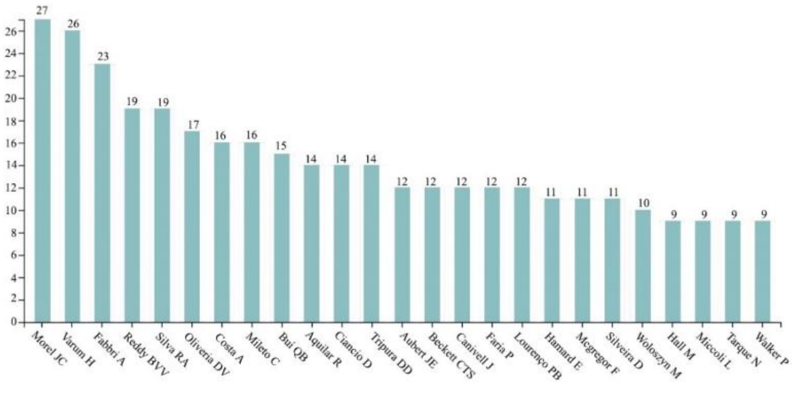

Figure 17. Distribution of 1.281 studies filtered through keywords in the "WOS" database according to the authors in the top 25.

Analysing the number of studies of the authors in 1,281 studies accessed in the Web of Science database, it was seen that the highest number of studies belonged to Morel, JC. with 27 and the lowest number of studies belonged to Hall, M., Miccoli, L., Tarque, N. and Walker, P. with 9. Looking at the graph, it is thought that the authors named Morel JC, Varum H., Fabbri A. come to the fore and the fact that the number of studies of the first 10 names are close to each other can create an important roadmap for future research on the subject.

4.3. Distribution of the Number of Studies by Research Topics

Figure 18 shows the distribution of the 1.281 data filtered through the "Web of Science" database according to the top 10 research topics.

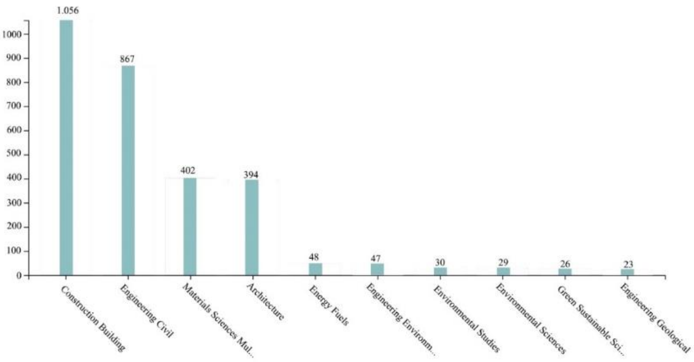

Figure 18. Distribution of 1.281 studies filtered through keywords in the WOS database according to research topics.

Analysing the research topics in the top 10 of the 1,281 studies accessed in the Web of Science database, it was found that the most studies were in the fields of construction building technology (1.056 studies), engineering civil (867 studies), materials science multidisciplinary (402 studies), architecture (394 studies), energy fuels (48 studies), engineering environmental (47 studies), environmental studies (30 studies), environmental sciences (29 studies), green sustainable science technology (26 studies) and engineering geological (23 studies).

4.4. Co-authorship Analysis

Figure 19 shows the relationship between the authors in 1.281 studies filtered through the "Web of Science" database.

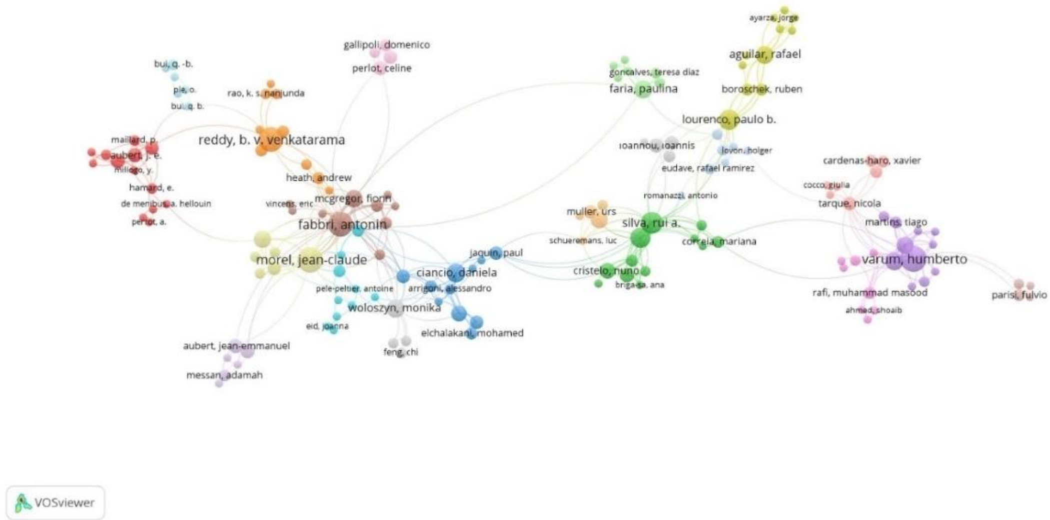

Figure 19. Co-author analysis of 1.281 studies filtered through keywords in the WOS database.

Co-authorship analysis via VOSviewer was performed by considering at least 2 articles with 1 author and at least 2 citations. The co-authorship analysis of 1,281 studies revealed 156 items, 20 clusters and 413 links. According to the results of the analysis, it is seen that there is a concentration in the clusters

Reddy B. V. Venkatarama, Fabbri Antonin, Morel Jean Claude, Silva Rui A., and Varum Humberto clusters. It is noted determined that the studies are mostly concentrated around the authors named Fabbri Antonin, Silva Rui A. and Varum Humberto.

4.5. Country Citation Analysis

Figure 20 shows the density of the countries mentioned in 1.281 studies filtered through the "Web of Science" database and their relationship to each other.

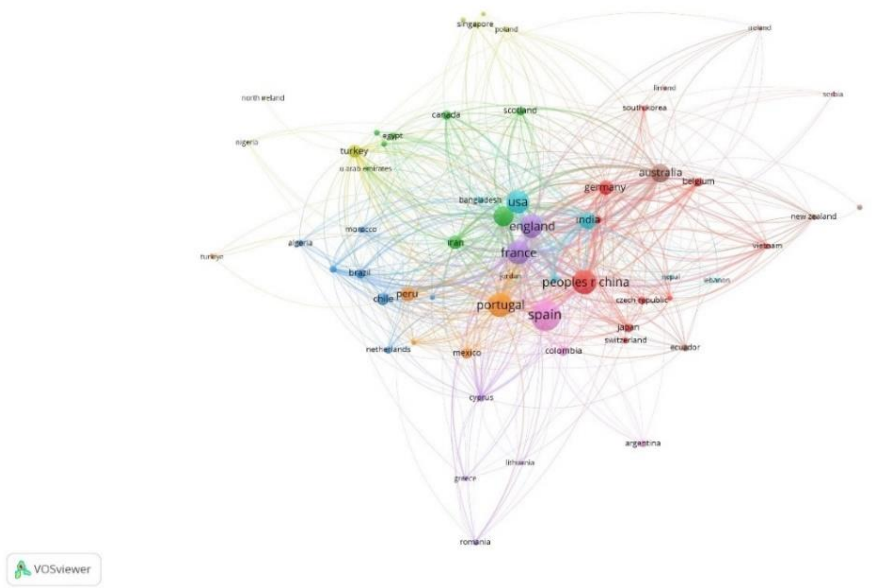

Figure 20. Country citation analysis of 1.281 studies filtered through keywords in the WOS database.

The country citation analysis via VOSviewer was based on the assumption that a country has at least 3 documents and at least 2 citations. The country citation analysis of 1.281 studies showed that there were 60 items, 10 clusters and 665 links. According to the results of the analysis, it was found that there is a concentration in the clusters USA, UK, France, Portugal, Spain and Peoples Republic China. The number of studies on the subject in the UK, France, Portugal, Spain and Australia are more numerous and cited more frequantly cited than in other countries. Looking at the cluster links, it can be seen that Turkey is not in the centre, but it has established links with countries that concentrate on the subject.

4.6. Keyword Analysis

Figure 21 shows the frequency of use of keywords in 1.281 studies filtered through the "Web of Science" database and their relationship with each other.

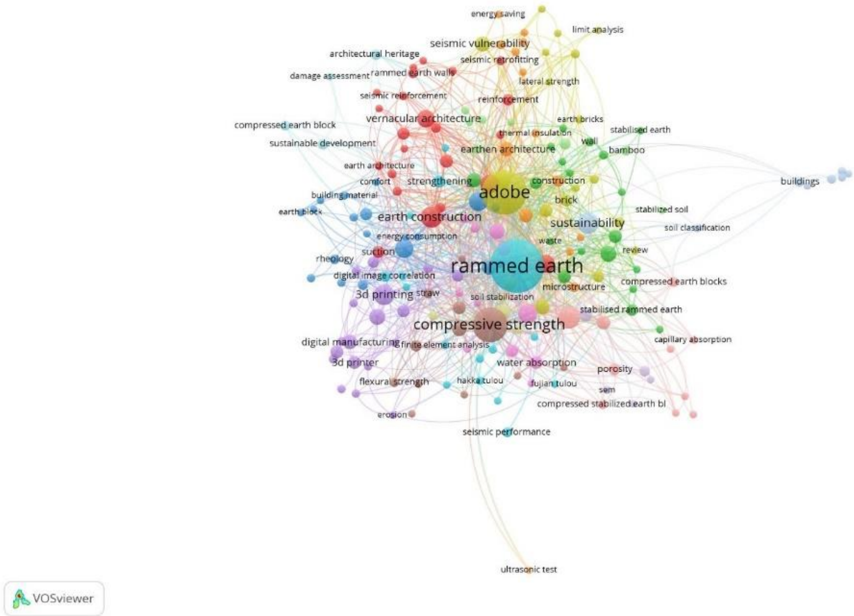

Figure 21. Keyword analysis of 1.281 studies filtered through keywords in the WOS database.

The frequency of co-occurance of keywords generated by VOSviewer is considered to be at least 4 common keywords. The keyword analysis of 1,281 studies identified 192 items, 16 clusters and 1,215 links were identified. According to the results of the analysis, it was determined that there is a concentration in the clusters of "adobe", "rammed earth" and "compressive strength" and that it is related to the words "sustainability", "earth construction" and "3D printing".

5. CONCLUSIONS

The integration of modern building technologies developed in the building construction industry with sustainable and low-cost building materials plays a major role in the inclusion of a local material such as earth in the digital innovation process. Therefore, computer-aided design tools, 3D printing systems, improved machine systems, CAD software and robotic arms offer significant advantages in the design and production process of contemporary earth structures. As a result of the literature review, it is understood that earth blocks and walls are produced faster and more efficiently with specialised compaction tools, extrusion machines and sliding mould systems, especially in the compaction technique used in the production of earth structures. For example, it is seen in the sections 2.1. (Stabilised Extruded Earth Blocks (Green Brick)) and 2.3 (Prefabricated Rammed Earth Walls) of the second part of the study (machine use and production process in the production of earth structures), it can be seen that earth structures can be included in prefabrication processes and that structures can be produced with a low margin of error thanks to extruders and the sliding mould system developed in Austria. In line with the examined examples of rammed earth structures studied, it was found that the developed technologies reduce the need for labour in the building production process and enable the production of more durable and large-scale projects. On the other hand, the integration of earth-based building materials such as clay with 3D printers paves the way for sustainable prototyping studies by offering different perspectives on the digitalisation of the earth. In this direction, 3D printers contribute to the parametric design of earth in complex geometric shapes. However, when clay, gravel and other additives are added to the earth mixture, it is clear that the current difficulties in the 3D printing system are particle sizes and that the mixture created in this direction should not be too solid or liquid. In addition, one of the main findings of the bibliometric analysis of 1281 studies examined on the subject, it is one of the most important findings that Spain, UK, Portugal and Australia are at the forefront, with the highest number of studies publishedin 2012. In addition, it is estimated that the authors named Morel JC, Varum H., Fabbri A. are at the forefront with the number of studies in the graph in the distribution of 1281 studies filtered through keywords in the 'WOS' database in Figure 17 according to the authors in the top 25 and that the number of studies of the first 10 names are close to each other will provide important clues for further research on the subject. Additionally, when the word analysis of 1281 studies showed that the clusters of 'adobe', 'rammed earth' and 'compressive strength' were central and were related to the words 'sustainability', 'earthen construction' and '3D printing'. In general, all modern applications have a positive impact on the design and production process of earthen buildings and there are many buildings built using these techniques around the world. As can be seen from the examples in the study, earthen structures are used not only in the construction of dwellings, but also in the production of various types of public buildings. The variety to different building types helps to avoid the perception of earth as a building material as 'traditional and weak building material. This study emphasises that the use of earth materials together with contemporary building technologies will contribute to a more sustainable building production today. Through theoretical and practical applications in contemporary earth building production, it is suggested that current limitations and challenges can be examined, and the problems of future research can be overcome.

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