DOI: https://doi.org/10.38027/iccaua2023en0342

Technological innovation in earth constructions: prefabrication and 3D printing.

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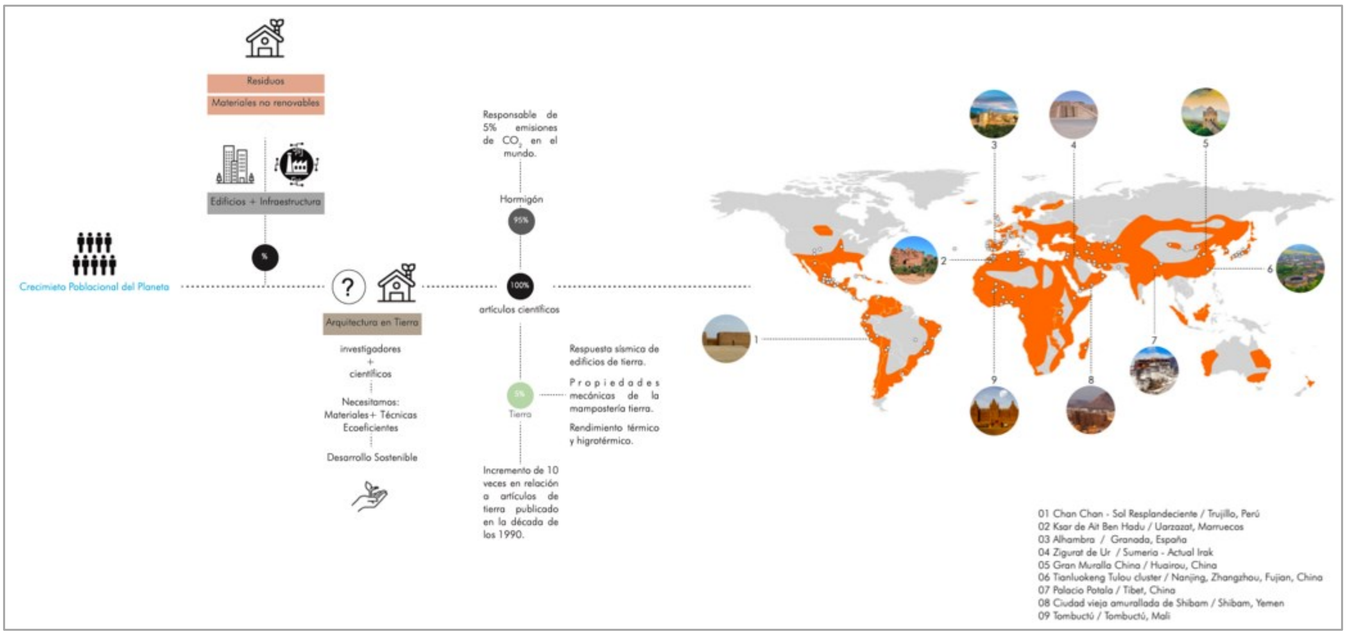
Abstract
This article focuses on the use and application of innovative technologies and tools in earth construction processes. It reviews the rammed earth construction system and its evolution towards prefabrication, as well as the use of earth as a raw material in the production of housing prototypes through 3D printing technology.
In order to validate earth construction as a modern and viable material, several recognized and award-winning works and prototypes at a global scale are collected and analyzed. These case studies utilize earth as the initial raw material for prefabrication and 3D printing, thus identifying the best technique that can be transferred to a developing country like Ecuador. The results of this research serve to highlight earth as a modern, alternative, and viable material that meets current demands for sustainability, energy efficiency, and housing deficit. Furthermore, its use in buildings can enhance thermal and acoustic performance due to its temperature and humidity regulation capabilities. Earth construction is also associated with promoting sustainable architecture and preserving cultural heritage. In conclusion, earth construction is a valuable option to address housing and sustainability challenges.
Keywords: earth construction, earthen architecture, clay, 3D printing with earth, rammed earth.

1. Introduction

Construction is one of the sectors that contributes the most to environmental pollution. With nearly 50% of the world's energy consumed, the extraction, transformation, and production of construction materials have a significant impact on the environment (Gomaa et al., 2023). To address this issue, researchers, architects, technicians, developers, and universities have conducted various studies on the environmental degradation caused by construction.
Among the proposed solutions, the use of materials such as earth stands out due to its low embodied energy and lesser industrial manufacturing. Additionally, the proximity of the material and construction techniques can be executed by the inhabitants themselves, making it a sustainable and cost-effective alternative. Despite the typical advantages of earth construction, one of the major issues faced by earthen architecture is its association with poverty, vernacular style, underdevelopment, and a lack of "status," which has led people to opt for conventional architecture (Guerrero Baca, 2011). However, countries like Germany, France, Italy, Spain, among others, have developed cutting-edge technology in earth construction, such as prefabrication and the use of 3D printers for constructing prototypes of earth-based housing.
In this context, the aim of this study is to analyze these existing technologies for possible implementation in a developing country like Ecuador and highlight the current state of earth as a construction material. The goal is to promote sustainable construction and the use of local materials, contributing to a reduction in environmental impact and an improvement in the quality of life for the population. Therefore, the use of earth as a construction material could be a sustainable solution to enhance the housing and environmental situation in developing countries like Ecuador.

2. Theoretical framework

Earthen construction is an ancient material used to build a wide variety of buildings and structures, from small villages to large religious monuments, and it remains the most commonly used building material worldwide (*CRAterre :: Accueil*, s. f.). Approximately one-third of the world's population lives in earth-based housing, and 17% of UNESCO World Heritage buildings are architectural works made of earth (*Accueil - amàco*, s. f.). Despite being used in construction for such a long time, earth remains a relevant and popular material today.
The United Nations (UN) expects that the world's population will increase from the current 7.7 billion to 9.7 billion by 2050, which poses two significant problems: the need for housing and infrastructure, and the increase in waste worldwide. To meet habitat needs in developing countries, Gernor Minke recommends using locally sourced construction materials and self-construction techniques. This approach shows that earth construction is an economical, sustainable, and environmentally friendly alternative. In the last decade, several research articles on earth construction systems have been published. However, this represents only a small fraction (less than 10%) of the research articles published on concrete. Research on concrete (the largest volume of manufactured material on Earth and responsible for 5% of CO2 emissions worldwide) has seen a ten-fold increase compared to research articles on earth construction published in the 1990s (Pacheco-Torgal & Jalali, 2012).



***Ilustration 1**. Current state of earth constructions.*

In 2010, the construction sector was responsible for 19% of total greenhouse gas emissions and accounted for 32% of global energy consumption. Heating and cooling systems represent 34% and 40% of energy consumption in residential and commercial buildings, respectively, and this consumption is directly related to the building envelope (Serrano et al., 2016). This awareness of creating a more sustainable planet has allowed for the reconsideration of earth as a modern construction material in developed countries. This is both encouraging and important because regions in developing countries adopt, replicate, and revalue the materials and methods of industrialized nations (Gatti, 2012; Amen, 2021; Aziz Amen, 2022; Amen et al., 2023; Amen & Nia, 2020).

3. Evolution in Earth Construction Systems: An Overview

In countries where raw clay is a common construction material, many of the techniques currently used have not been significantly modified or innovated (Calderón, 2019), However, earth construction has experienced a resurgence worldwide in recent years. The local availability of raw materials, low embodied energy, and its potential for recycling strengthen the material in the context of circular economy development (François et al., 2017). On the other hand, research, appreciation, innovation, preservation, and application of earth as a modern construction material have been key to rediscovering a material that was almost forgotten during the 20th century.

Raw earth offers architects plastic qualities, thermal control through its mass, water balance, textures, and colors, turning their projects into sculptural works (*15-SIACOT-Ecuador-2015.pdf*, s. f.). Current projects have successfully modernized traditional earth construction techniques to adapt them to design and construction needs.

3.1.1 Industrialization of Rammed Earth

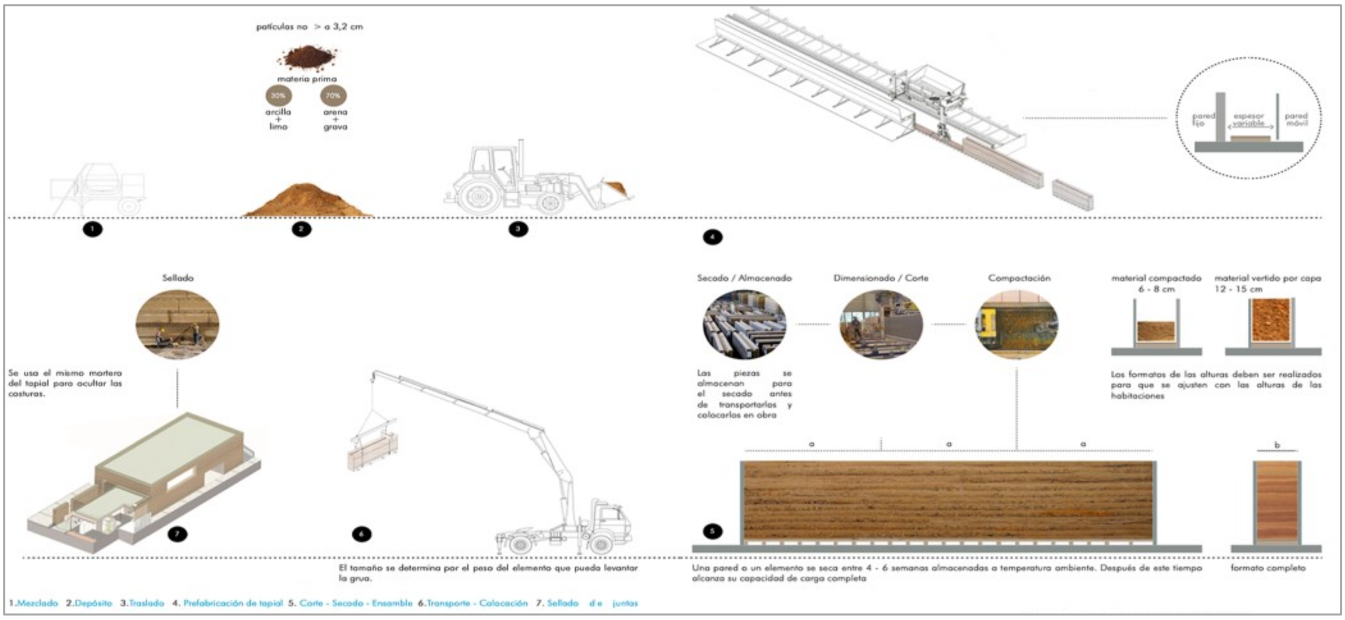
In recent years, earth constructions have been revalued from two distinct perspectives. In Asia, Latin America, Africa, and the Middle East, earth constructions are used for social housing and emergency housing. In Europe, the focus is on raw earth as a sustainable material for new constructions (Giuffrida et al., 2019a).

One of the earth construction systems that has seen significant development in recent years is rammed earth. This construction technique manually compacts moist earth within wooden formwork using wooden rammers. In the last few decades, this production process has been improved through the use of continuous metal formwork and pneumatic rammers, significantly enhancing mechanical characteristics and production speed. While equipment and tools developed for concrete are used to build rammed earth walls, these processes still require a significant amount of labor, which is not realistic in many industrialized parts of the world where labor is costly. In such contexts, prefabrication is more suitable (Heringer et al., s. f.).

Among the most prominent pioneers in evolving the rammed earth construction system, from traditional to prefabrication, is the company Lehm Ton Erde. This company has developed tools, types of formwork, natural material mixes, more efficient methods for earth compaction, new work techniques, test walls, as well as ways to "control" material erosion in adverse weather conditions. Over the course of three decades of studies and experiments, technical advancements and improvements have aligned with formal complexity, rearticulating a craft language of rammed earth to contemporary architectural standards (Perez, 2019). Ultimately, this company has developed alternatives for earth walls ranging from dividing modules to modules containing ventilation ducts powered by a geothermal heat collector: the earth walls function as hypocausts(*Loam Clay Earth, Martin Rauch, Vorarlberg*, s. f.).

3.1.2 The potential of prefabrication

Prefabrication can solve many problems related to earth construction: Correction and optimization of the base material (soil); Control over the combination of different natural base materials (soils, sands, other aggregates); Repetition of the manufacturing process; Control over the physical, thermal, and mechanical characteristics of materials and products through experimental testing; Control over actual durability using experimental tests (Giuffrida et al., 2019b). Prefabrication with earth is still a recent and largely unexplored technique. Besides the advantages that can be obtained, this technique allows for the consistency of the material, which is important to achieve industrialized standards and quality (Heringer et al., s. f.) Prefabrication processes are primarily aimed at reducing the amount of physical labor. However, planning and production processes must be closely coordinated and studied in the design and planning stage to avoid issues during construction. It is also important to standardize the details of earth prefabricated elements. This allows the prefabricated earth elements to fit into existing construction details. The prefabrication process does not require a human team as in on-site construction. The processes of preparation, manufacturing, transportation, and installation become mechanized, and the use of machinery becomes essential (Pan, s. f.) Furthermore, in cases where a project requires a large volume of walls, it is advisable to establish local factories to use regional materials and avoid significant transportation distances.

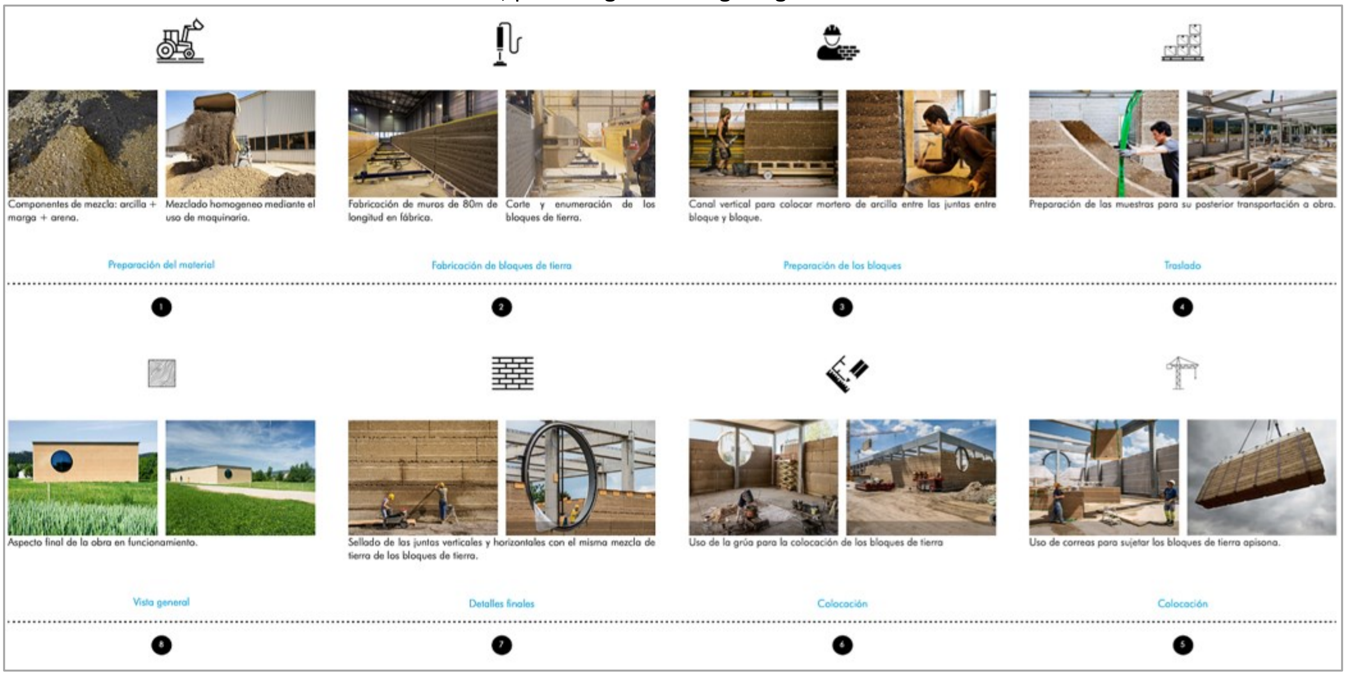


Ilustration 2 Prefabrication process of rammed earth

3.1.3 Prefabricated rammed earth as a project material: Ricola Kräuterzentrum.
Location: Laufen, Suiza
Project area: 4 800 m^2
Construction: 2013
Author: Herzog & de Meuron
Construction technique: Prefabricated rammed earth/unstabilized/non-load-bearing
Earth construction: Lehm Ton Erde Baukunst GmbH, Martín Rauch

Ilustration 3 Ricola Kräuterzentrum

The Ricola Kräuterzentrum is an herb processing center that encompasses activities from drying and cutting to mixing and storage. The building features a reinforced concrete structure and self-supporting rammed earth walls, 45 cm thick, manufactured in a nearby industry. 666 rammed earth blocks, measuring 3 meters in length and 1.2 meters in height, were used, with an apparent density ranging from 1700 to 2200 kg/m³. Some of the excavated material from the site was also used in the construction.
With a length of 111 meters, width of 30 meters, and height of 11 meters, this building is considered the largest in the world built with clay. To prevent erosion caused by wind and rain, a layer of volcanic tuff and lime mortar was applied every 8 layers of earth. The entire enclosure rests on a 30 cm thick concrete foundation. The choice of earth as the enclosure material was based on its ability to maintain a constant humidity of 50% inside the building. Additionally, the building facades feature windows anchored to the rammed earth walls, providing natural lighting to the interior.



Ilustration 4 Cosntruction process of the building Ricola Kräuterzentrum

3.2.1 Digital Construction: 3D Printing

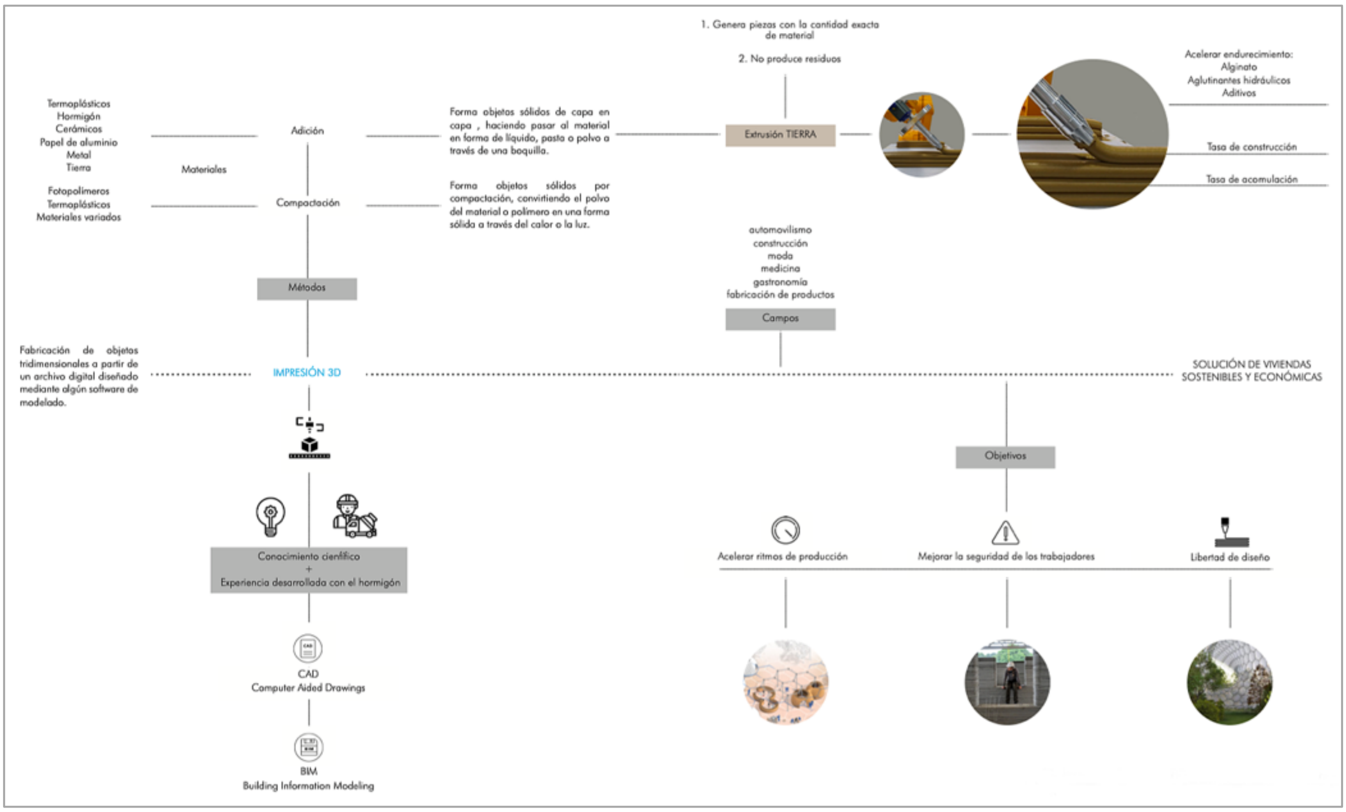
We are in a technological era of robots, artificial intelligence, and machine learning. 3D printing is the manufacturing of three-dimensional objects from a digitally designed file using modeling software. This accelerated technological evolution has allowed for the discovery, development, and improvement of tools that facilitate human activities on Earth. In this perspective, the inclusion of 3D printers in the field of construction is a clear response to meet the housing demands on the planet.

While it is true that other areas of knowledge are heavily investing in 3D printing to overcome obstacles, the construction market is still taking its first steps in this new concept (Goodbun, 2016). Nevertheless, three-dimensional printing technology is being considered as the technology that can be used to autonomously print constructions on the Moon or Mars in order to avoid the transportation of construction material from Earth. In this case, the constructions in those instances would be produced using on-site materials (Pacewicz et al., 2018)

Currently, there are constructions made with this technology. The projects range from houses to complex space structures, pavilions, cabins, offices, bridges, and pieces with complex geometries or rapid prototypes of objects (Kontovourkis & Tryfonos, 2020) Three-dimensional printing technology can provide significant benefits compared to conventional construction, including automation of construction processes, reduction in labor, cost reduction, formal freedom, and the avoidance of additional supports such as formwork (Wu et al., 2016) Additionally, it aims to streamline the execution and assembly processes of parts and products, especially after events such as building collapses or falls, terrain instability, and other construction-related aspects.

The materials used in this technology include fiber-reinforced concrete, thermoplastics, plastics, geopolymers, and recently, earth and natural waste from the rice production chain. (Naldoni et al., 2018) These materials not only contribute to reducing construction time but also offer solutions with lower environmental impact and recyclability (Kontovourkis & Tryfonos, 2020)

The evolution of these earth construction techniques demonstrates the value of earth not only for self-construction but also for industrialized construction, allowing the use of earth as the primary raw material in the development of these new fields of science and greatly enhancing its revaluation as a material. The combination of ancient and modern elements could offer relevant and sustainable solutions to meet the growing demand for housing on the planet in the coming years.



Ilustration 5 3D printing technology with earth

3.2.2 First eco-sustainable home 3D-printed with earth: Casa Gaia

Location: Massa Lombarda, Italia
Project area: 12 m2
Construction: 2013
Author: WASP & RiceHouse
Construction technique: 3D printed/non-load-bearing
Earth construction: 3D CRANE WASP

Ilustration 6 Gaia House

Gaia is a prototype of an eco-sustainable home, pioneering in its use of natural materials and earth, and built through 3D printing in a collaboration between the companies WASP and RiceHouse. WASP developed a special printing system for the project, while RiceHouse supplied natural fibers derived from rice.
To construct the 40 cm thick walls, WASP used a mixture composed of 25% local soil (30% clay, 40% silt, and 30% sand), 40% chopped rice straw, 25% rice husk, and 10% hydraulic lime. The empty spaces were filled with natural shells, and the interior walls were smoothed with a layer of clay, protected with linseed oil.
Thanks to its southwest orientation, the home maximizes solar energy utilization, and the earth envelope helps maintain a comfortable temperature inside, reducing the need for heating and air conditioning. The prototype was built in just 10 days and has an estimated cost of €900.

Ilustration 7 Construction process of Gaia House

4. Discussion

While it is true that earth is a sustainable, eco-friendly, and low-energy material incorporated in its construction process, I consider the reuse of machinery to be somewhat absurd. However, I believe that with technological advancements, we can overcome these difficulties and avoid further pollution. Perhaps we could start using machinery and tools that generate a lower carbon footprint, which would make the use of technology in sustainable construction more environmentally friendly.

Although notable examples like the Ricola Kräuterzentrum and Casa Gaia demonstrate the potential of earth as an architectural material, I believe that the construction process behind these houses still needs improvement in terms of sustainability. Nevertheless, these two projects are just examples among many others that show that younger generations are more aware of the need to explore construction with sustainable elements, materials, and tools, always aiming to leave a better world for future generations.

The Ricola Kräuterzentrum building, although not the most prominent, represents a significant contribution to the field of earth architecture. From an architectural standpoint, it is elegant and contemporary, departing from the typical earth construction that has prevailed in architectural history. Similarly, I believe that Casa Gaia represents an almost complete break from manual construction. This may become more relevant in the future, given the rapid advancement of technologies. It is possible that in the not-so-distant future, we will have the necessary equipment for its execution. This 3D printing technology is even being studied for use on Mars with locally available materials, indicating that its implementation may be closer than we imagine.

Over the past few decades, we have witnessed a resurgence of sustainable construction worldwide. It is our obligation to continue the necessary research to find quick solutions to scarcity and pollution issues before it is too late.

5. Conclusions

Prefabrication on land is a technological advance and is a step towards the modernization of the material, its implementation allows obtaining advantages in the quality control processes of the material, reducing execution times, calculating the performance of execution and reduction of tools on site. Among the drawbacks of this technique is handling and transport in areas with difficult conditions or lack of infrastructure.

3D earth prints are not just a sample of the advancement of digital technology developed by a company, but rather are examples that highlight the earth as a material that has allowed the weaving of a network of researchers, technology companies, startups, and people who are committed to a change in the planet.

Through this research, the coexistence between earth and technological innovations and a renaissance of architecture on earth in a digital age have been confirmed. It should also be noted that this resurgence of the material is not located in a certain geographical area but on a global scale. However, it is important to mention that these prefabrication and 3D printing technologies are relatively recent in the field of constructions with earth and are built in developed countries that can significantly influence developing countries.

However, technical limitations and the absence of an industry that works on the development of these technologies generates a limitation in the expansion of constructions on land. In this sense, the academy plays an important role, which is to generate content and study curriculum that respond to the planet's environmental emergencies and satisfy the needs of more sustainable and affordable habitats for human beings. It is contradictory to talk about sustainability if we continue using materials such as concrete, steel, aluminum that incorporate large amounts of energy in their manufacturing processes.

Conflict of Interests

The author declare no conflict of interest.

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