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Towards an Applied Scientific Methodology to Enhance Sustainable Local Architecture Using 3d Printed Buildings with Recyclable Materials (A Case Study of Siwa Oasis in Egypt)

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ABSTRACT

Three-dimensional printed buildings offer numerous advantages compared to traditional construction methods. They provide higher efficiency and faster execution, contributing to reduced time and effort in the construction process. Additionally, they can be designed and built using recyclable and environmentally friendly materials, promoting environmental sustainability and cost reduction. They can be engineered to withstand earthquakes and natural disasters and possess the capability to address current environmental challenges such as climate change and the energy crisis. The aim of this research is to develop an applied scientific methodology for the design and implementation of three-dimensional printed buildings using recyclable and environmentally friendly materials in Egypt. This will be achieved by leveraging a comparative scientific approach that studies global and regional experiments in this field, with the objective of adapting and implementing this methodology in Egypt, particularly in special regions like Siwa Oasis. The research will also utilize artificial intelligence applications and mathematical equations to enhance outcomes and achieve success in this advanced and innovative field.

KEYWORDS: 3D printed buildings, Recyclable materials, Sustainable local architecture, Artificial intelligence, sustainable materials

نحو منهجية علمية تطبيقية لتعزيز العمارة المحلية المستدامة باستخدام المباني المطبوعة ثلاثية الابعاد بالمواد المعاد تدويرها (دراسة حالة واحة سيوة في مصر)

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الملخص :

توفر المباني المطبوعة ثلاثية الأبعاد العديد من المزايا مقارنة بطرق البناء التقليدية . فهي تتمتع بكفاءة أعلى وتمتاز بسرعة التنفيذ، مما يساهم في تقليل الوقت والجهد المبذولين في عملية البناء. بالإضافة إلى ذلك، يمكن استخدام المواد المعاد تدويرها والصديقة للبيئة في تصميم وبناء المباني المطبوعة

ثلاثية الأبعاد، مما يعزز الاستدامة البيئية ويخفض التكاليف. ويمكن تصميمها بشكل يسمح لها بمقاومة الزلازل والكوارث الطبيعية، والقدرة على مواجهة التحديات البيئية الحالية مثل تغير المناخ وأزمة الطاقة.لذا يهدف هذا البحث إلى الوصول إلى منهج علمي تطبيقي لتصميم وتنفيذ المباني المطبوعة ثلاثية الأبعاد باستخدام المواد المعاد تدويرها والصديقة للبيئة في مصر. مع الاستعانة بالمنهج العلمي المقارن لدراسة التجارب العالمية والإقليمية في هذا المجال، بهدف تكييف وتنفيذ هذا المنهج في مصر ، وبخاصة في المناطق ذات الطابع الخاص مثل واحة سيوة. عن طريق الاعتماد علي تطبيقات الذكاء الاصطناعي والمعادلات الحسابية لتعزيز النتائج وتحقيق النجاح في هذا المجال المتطور والمبتكر.

الكلمات المفتاحية : المباني المطبوعة ثلاثية الأبعاد ، مواد معاد تدويرها ، العمارة المحلية المستدامة ، الذكاء الاصطناعي ، المواد المستدامة

1. INTRODUCTION

The sustainable local architecture and the use of 3D printing technology with recycled materials can be considered a promising option for achieving environmental sustainability and meeting the needs of local populations. With the advancement of technology, availability of resources, and appropriate training, these methods can become more widespread and effective in the future [1].

The use of 3D printing technology with recycled materials enables the creation of buildings with complex shapes and designs, allowing for the design of structures that are in harmony with the local environment and reduce the reliance on new raw materials such as natural aggregates, which require significant energy-intensive extraction and manufacturing processes. By preserving natural resources, carbon emissions associated with extraction [2].

2.THE MAIN OBJECTIVE OF THE RESEARCH

Through the application of a design methodology aimed at leveraging digital manufacturing tools, the research aims to develop an architectural approach that combines recycled materials and their use in printed buildings to design structures that reflect local identity and promote sustainability.

3. SUSTAINABILITY AND LOCAL BUILDING MATERIALS

The concept of sustainability aims to empower individuals worldwide to meet their basic needs and enjoy a better quality of life without compromising the ability of future generations to meet their own needs. In the realm of construction, traditional practices relied heavily on the utilization of natural materials such as stone, clay, wood, and thatch. These materials have been found to possess positive environmental attributes, including a lack of contribution to the greenhouse effect, suitability for local environmental conditions, recyclability, and favorable impacts on public health. By embracing green building materials, several advantages can be achieved, including reduced maintenance and replacement costs throughout the lifespan of a building, enhanced energy efficiency, decreased expenses associated with altering spatial configurations, and unrestricted design flexibility [3] shown on **Fig. 1.**

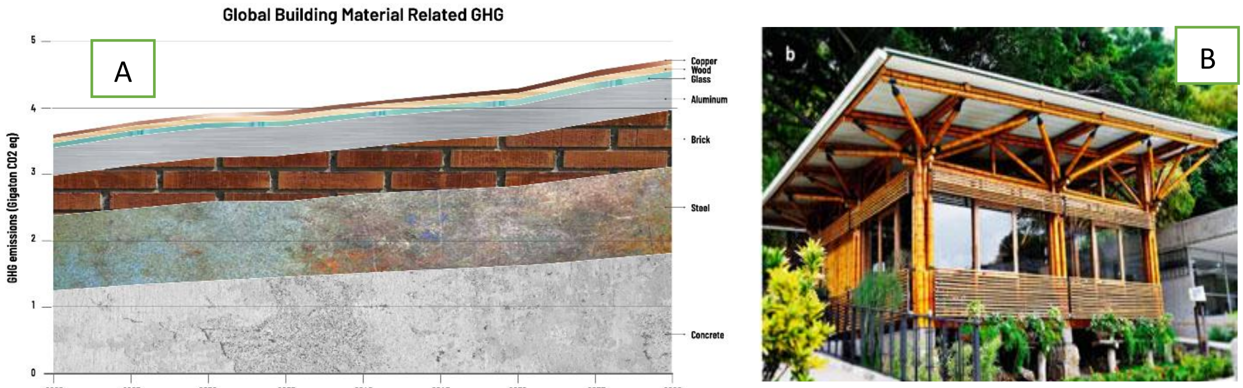


Fig. 1. (A) Global building material related GHG ; (B) Example for Eco house source [4]

4. CONSTRUCTION 3D PRINTING:

3D printing is a manufacturing process characterized by the incremental addition of materials, layer by layer, guided by a digital model, with the ultimate objective of fabricating a three-dimensional structure. shown on **Fig. 2.** This innovative technique offers notable advantages, including the reduction of both time and resource consumption compared to conventional manufacturing approaches. Moreover, 3D printing enables the production of intricate designs that are otherwise unattainable through traditional methodologies [5].

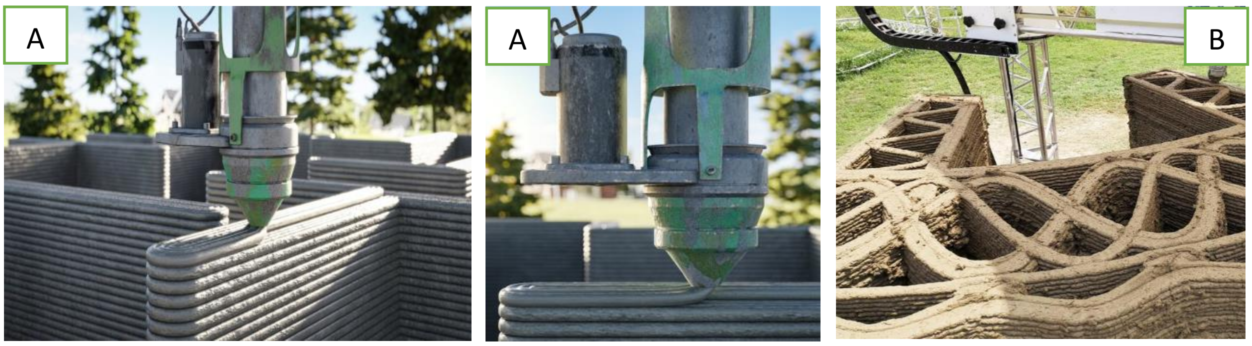


Fig. 2. (A) And (B) example construction 3d printing source [6].

4.1 TYPES OF 3D PRINTING TECHNOLOGY USED IN CONSTRUCTION: [7]

A-Robotic Arm Extruders : resembling cranes in their configuration, represent a prevalent contouring method employed in additive manufacturing. This technique involves the coordinated movement of a robotic arm, which progressively deposits material, such as concrete or polymers, layer by layer, thereby facilitating the construction of three-dimensional structures. To achieve precise deposition in a predetermined pattern, shape, and thickness, the robotic arm of a 3D printer can be meticulously operated through computer-aided design (CAD) software. Shown on **Fig. 3 [A].**

B- Gantry System: In the realm of construction, a gantry 3D printer signifies a sizeable additive manufacturing device that employs a gantry system for traversing the print head across the X, Y, and Z axes. These systems are frequently adopted by construction entities engaged in the 3D printing of expansive structures and buildings. Shown on **Fig. 3 [B].**

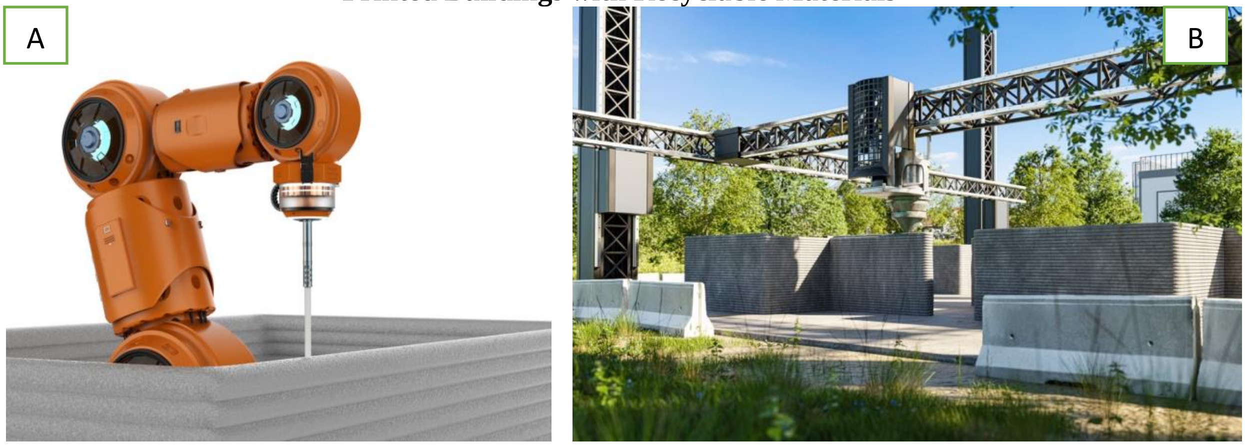
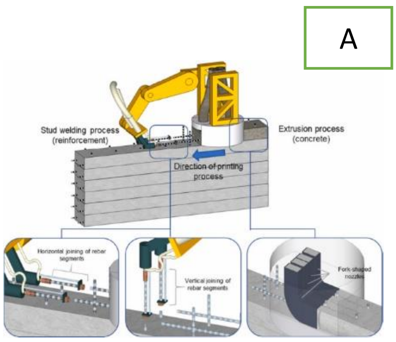
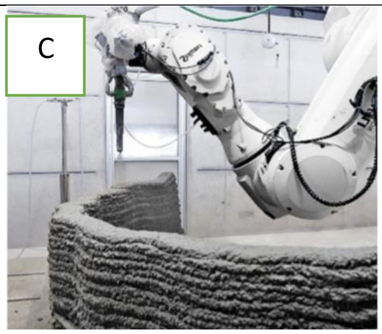


Fig. 3. (A) Robotic Arm Extruders; (B) Gantry System source [8].

4-2 METHODS USED FOR 3D PRINTING FOR CONSTRUCTION :

Here are some of the most common 3D printing methods in construction shown on Table **1.**

Table 1. (A) (B) (C) (D) Methods Used for 3D Printing for Construction source [9].

METHODS	DESCRIPTION	IMAGE
Extrusion	The extrusion method is widely employed in the construction industry as the predominant 3D printing technique. It entails the controlled deposition of materials through one or more nozzles affixed to a robotic arm, gantry system, or crane. This versatile method can be utilized across various environments and finds frequent application in modeling, prototyping, and production processes.	
Powder Bonding	Powder bonding is a distinct 3D printing approach that distinguishes itself by employing powdered material as its primary constituent. This method encompasses two subcategories: powder bed jetting and binder jetting.	
Spray Technique	The spray technique involves use of an independent robot that selectively sprays pressurized construction material onto the desired shape, repeating the process layer by layer. This method creates voids that can subsequently be filled with concrete. Currently, research is underway to explore the application of this technique for vertical elements and architectural features such as façades or decorative ceilings.	

Sand Layers	The sand layer method employs the sequential deposition of layers of sand to construct a desired structure. The printer releases sand grains until the desired thickness is achieved, after which droplets of a bonding agent are dispensed to harden and bind the sand particles together. This technique is particularly suitable for fabricating small-scale structures or building components. One notable advantage of utilizing sand layers is that the materials employed in this technique are often inexpensive and readily available. Furthermore, it is a relatively straightforward method that requires less specialized equipment compared to certain other 3D printing methods.	D 

5- THE RELATIONSHIP BETWEEN SUSTAINABILITY AND 3D-PRINTED BUILDINGS :

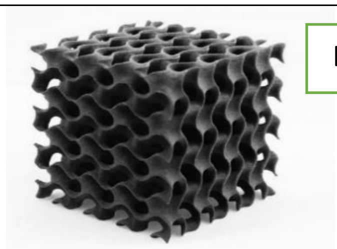
5-1 Improved energy efficiency :

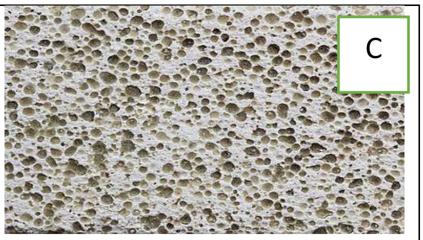
3D-printed buildings can be designed to be more energy-efficient. Innovative designs for thermal insulation and ventilation can be incorporated into the printing process, reducing energy consumption for heating and cooling and enhancing the building's comfort. [10]

5-1-1 3D printed thermal insulating materials :

are such materials that do not allow the movement of heat through themselves. The material must have lower thermal conductivity to work efficiently as an insulator Shown on **Table 2.**

Table 2. (A) (B) (C) 3D printed thermal insulating materials source [11].

Name of materials	description	Image
1- Aerogel	Aerogels are lightweight materials known for their extremely low density and high porosity. They are typically composed of a solid network of interconnected nanoparticles or fibers suspended in a gas or liquid. In 3D printing, aerogels can be incorporated into the printing material or used as a standalone material for creating intricate structures.	A 
2- Gyroids	also known as gyroid structures or gynocidal lattices, are complex geometric structures that exhibit unique properties, such as high strength-to-weight ratios, excellent mechanical properties, and good thermal and electrical conductivity.	B 

3- Geopolymeric foams	is a class of inorganic polymers made from the reaction of aluminosilicate materials with alkaline activators. Geopolymeric foams are lightweight materials with cellular structures that offer a range of desirable properties	

5-2 printed thermal insulating application:
Using double wall technique shown on **Fig. 4.**

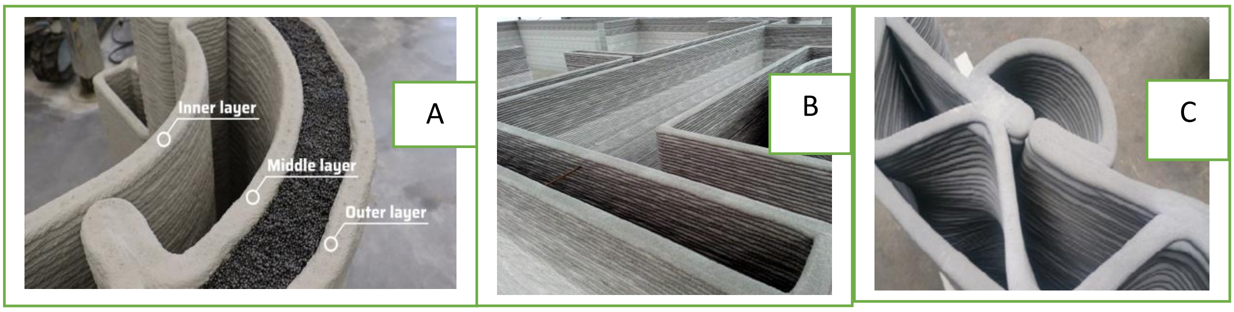


Fig. 4. (A)(B)(C) double wall technique source [12].

5-3 RELATIONSHIP BETWEEN 3D PRINTED AND NATURAL LIGHTING :

5-3-1 Transparent concrete:
is produced using fine materials without the inclusion of coarse aggregates. It possesses a compressive strength comparable to that of high-strength concrete One of the main advantages of transparent concrete is its ability to transmit light due to the incorporation of light-transmitting optical fibers or particles within its matrix. These optical elements allow for the passage of light through the concrete, resulting in a translucent.
Using 3D printing, unique architectural designs can be achieved with the use of transparent concrete. The transparent material can be loaded into 3D printed molds to create walls, facades, and other building elements with intricate shapes and fine details. This allows for the integration of transparent concrete and 3D printing technology in the creation of innovative building constructions. [13] **shown on Fig. 5.**

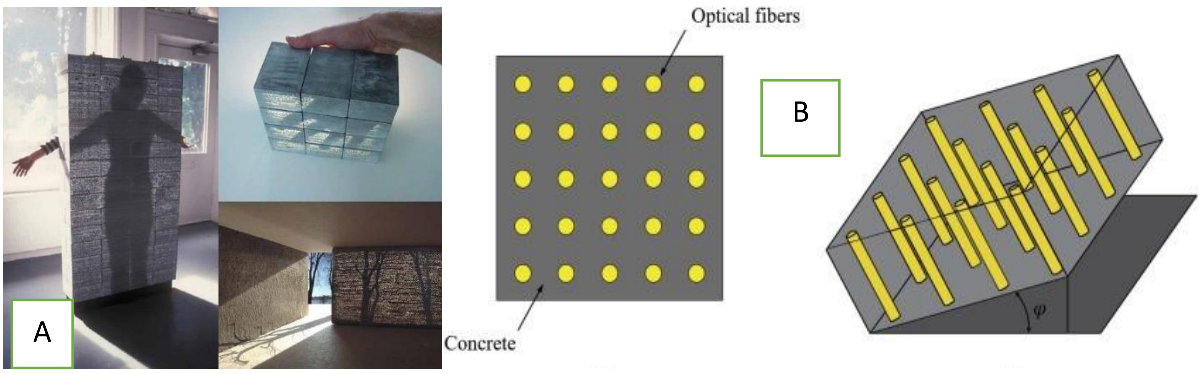


Fig. 5. (A) and (B) Transparent concrete source [14]

5-3-1-1 imagination relationship between 3D printed and Transparent concrete with Ai:

using look x application generation shape use code shown Fig. 6.

Transparent concrete, Material that allows light to pass through , Made by adding optical fibers or other light-transmitting materials to concrete mix , Applications: Building facades, interior walls, flooring, furniture

Fig. 6. imagination relationship between 3D printed and Transparent concrete with Ai
source researcher

5-3-2 LUMINOUS CEMENT :

that possesses the unique ability to emit light, thereby offering a remarkable solution for illuminating roads and buildings without the need for electrical equipment. The luminous properties of this cement are achieved through a meticulous process of microstructural modification, which results in a distinctive surface texture capable of capturing and storing light energy. According to the creator of this material, when exposed to sunlight for a duration of 12 hours, it has the capacity to emit light for an equivalent period. This development holds significant potential for enhancing the sustainability and energy efficiency of various infrastructures. The luminous cement presents a promising alternative to conventional lighting systems, as it harnesses the power of natural light and eliminates the reliance on electricity for illumination purposes. Furthermore, the extended duration of light emission contributes to enhanced visibility and safety during nighttime hours [15] shown on **Fig. 7.**

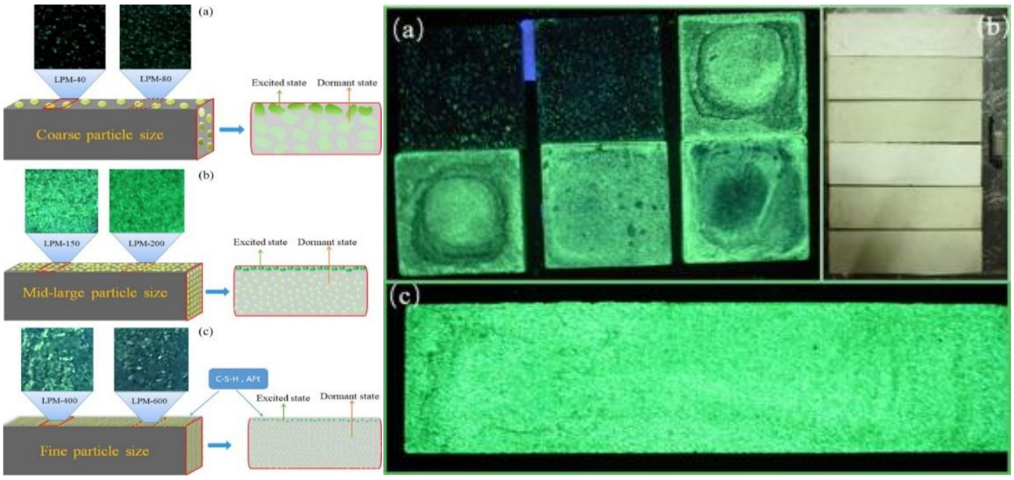


Fig. 7. Luminous Cement source [16]

5-3-2-1 imagination relationship between 3D printed and Luminous Cement with Ai:

using look x application generation shape use code shown Fig. 8.

Photo luminescent cement , Fluorescent cement , Glow-in-the-dark cement, Luminescent concrete , Light-emitting concrete

Fig. 8. imagination relationship between 3D printed and Luminous Cement with Ai source researcher

6- RECYCLED MATERIALS USING ON 3D PRINTING:

are increasingly being used in 3D printing to promote sustainability and reduce waste. Here are some examples of recycled materials commonly used in 3D printing [17] shown **Table 3.**

Table 3. (A) (B) (C) (D) (E) Recycled Materials using on 3d printing source [18].

NAME OF MATERIALS		DESCRIPTION	IMAGE
Manufactured Off Site	**1- Recycled PLA (Polylactic Acid):**	a biodegradable and compostable thermoplastic derived from renewable resources such as corn starch or sugarcane. Recycled PLA is made by collecting and processing discarded PLA products or waste prints and transforming them into new filament for 3D printing.	 A
	2-Recycled PET (Polyethylene Terephthalate)	Recycled PET filament is produced by collecting and processing post-consumer PET bottles and converting them into a usable form for 3D printing	 B

	3- Recycled ABS (Acrylonitrile Butadiene Styrene)	ABS is a durable and impact-resistant thermoplastic often used in industrial applications. Recycled ABS filament is created by collecting and processing discarded ABS products or waste prints and transforming them into filament suitable for 3D printing.	
Excavated Materials	**4- Rice waste**	Rice waste made up 65 percent of the materials used to print the Gaia house	
	5-recycle concrete	Applying Recycled Coarse Aggregate (RCA) in the preparation of 3D Printed Recycled Coarse Aggregate Concrete (3DPRAC) offers advantages, as it not only facilitates a reduction in cement and natural aggregates (both coarse and fine aggregates), leading to cost savings on raw materials, but also mitigates the carbon footprint.	

6-1 BUILDING MATERIAL COMPOSITION FOR 3D PRINTING AND PROPERTIES REQUIREMENTS:

The development and utilization of materials for 3D printing technology in construction rely on a complex interplay of three key factors: raw materials, application methods, and production techniques. When designing such materials, careful consideration must be given to the specific properties that the printed object needs to possess, as well as the capabilities of the chosen printer. [19]

One crucial aspect to consider is the availability of locally sourced raw materials in close proximity to the construction site. This consideration ensures that the transportation costs associated with obtaining these materials remain economically feasible. Moreover, the composition of the material mixture is influenced by the prevailing climatic conditions at the site of object production, as these conditions impact the composition of the mixture and the curing requirements [20] Shown **Fig. 9.**

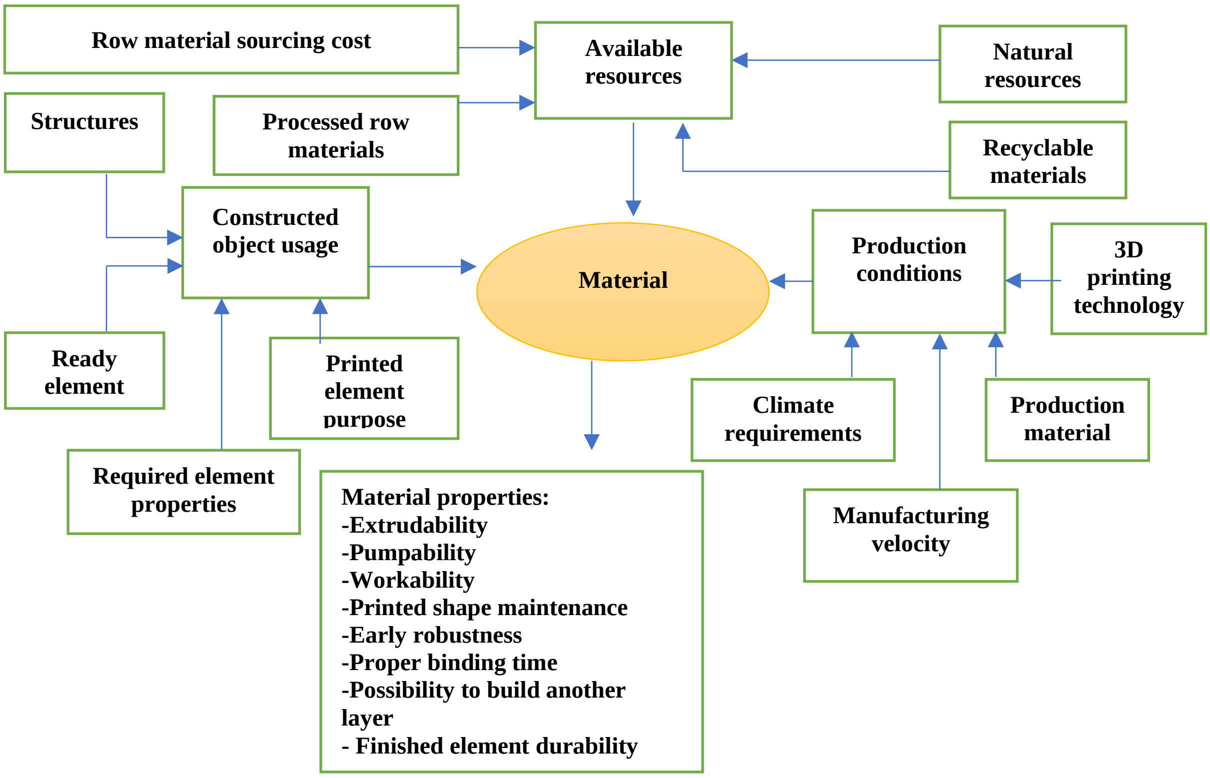
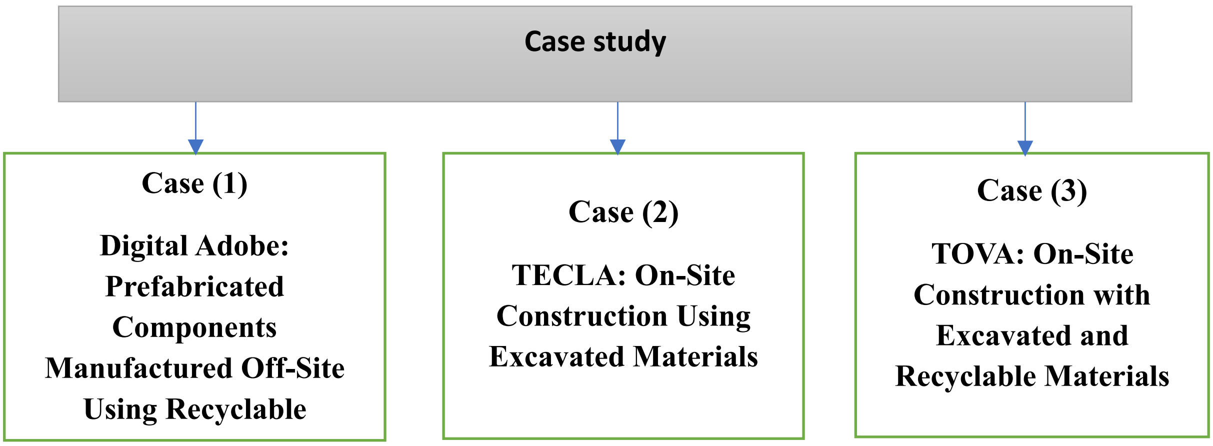


Fig. 9. Building material composition for 3D printing and properties requirements source [21]

7- CASE STUDY:



7-1 DIGITAL ADOBE: PREFABRICATED COMPONENTS MANUFACTURED OFF-SITE USING RECYCLABLE MATERIALS:

This study encompasses a 2-meter-wide and 5-meter-high printed clay wall with a variable thickness, measuring 0.7 meters at the base and 0.2 meters at the top. A wooden slab is positioned at a height of 2.6 meters, simulating a clay/wood building unit and facilitating the examination of material connections and vertical load distribution from a horizontal slab. The Digital Adobe project represents a pioneering large-scale investigation into the integration of 3DPE (3D Printed Earth) and wooden elements, wherein the 3D-printed earthen component bears the compressive load of the structure, while the wooden spanning element functions under tension .The primary objective of this case study was to explore the climatic and structural performance of Leveraging the well-established knowledge regarding clay's thermal properties in heat moderation, the team aimed to develop a design that enhances these characteristics. To minimize temperature transfer across the wall and enhance its compressive strength, the infills were filled with unprocessed soil. A ventilated wall design was implemented to reduce heat gain during summer through convection between the openable top and bottom openings, while still retaining heat during winter when both openings were closed [22] shown on **Fig. 10.**

Fig. 10. Digital Adobe source [22]

7-2 TECLA: ON-SITE CONSTRUCTION USING EXCAVATED MATERIALS :

TECLA (WASP 2022) is an innovative circular housing unit that was constructed in Massa Lombard by WASP and Mario Cucinella Architects (MCA), combining research on vernacular building techniques with the use of natural and regional materials. The construction of TECLA involved the simultaneous operation of two printer arms, synchronized through industrial automation protocols to optimize mobility, prevent collisions, and ensure efficient performance. With a floor area of 60 square meters, TECLA features a sinuous and uninterrupted sine curve design, culminating in two circular skylights that provide zenithal lighting. Moreover, the composition of the earth mixture used in TECLA was carefully selected to respond to local climatic conditions. The filling of the building envelope was parametrically optimized to achieve a balance between thermal mass, insulation, and ventilation, tailored to the specific climate requirements. The materials employed in the construction included local soil with a maximum aggregate size of 6 mm, sand, rice husk, and Mapes oil, a lime-based binder added at a weight percentage of 5% per batch [23] shown on **Fig. 11.**

Fig. 11.TECLA project source [23]

7-3 TOVA: ON-SITE CONSTRUCTION WITH EXCAVATED AND RECYCLABLE MATERIALS :

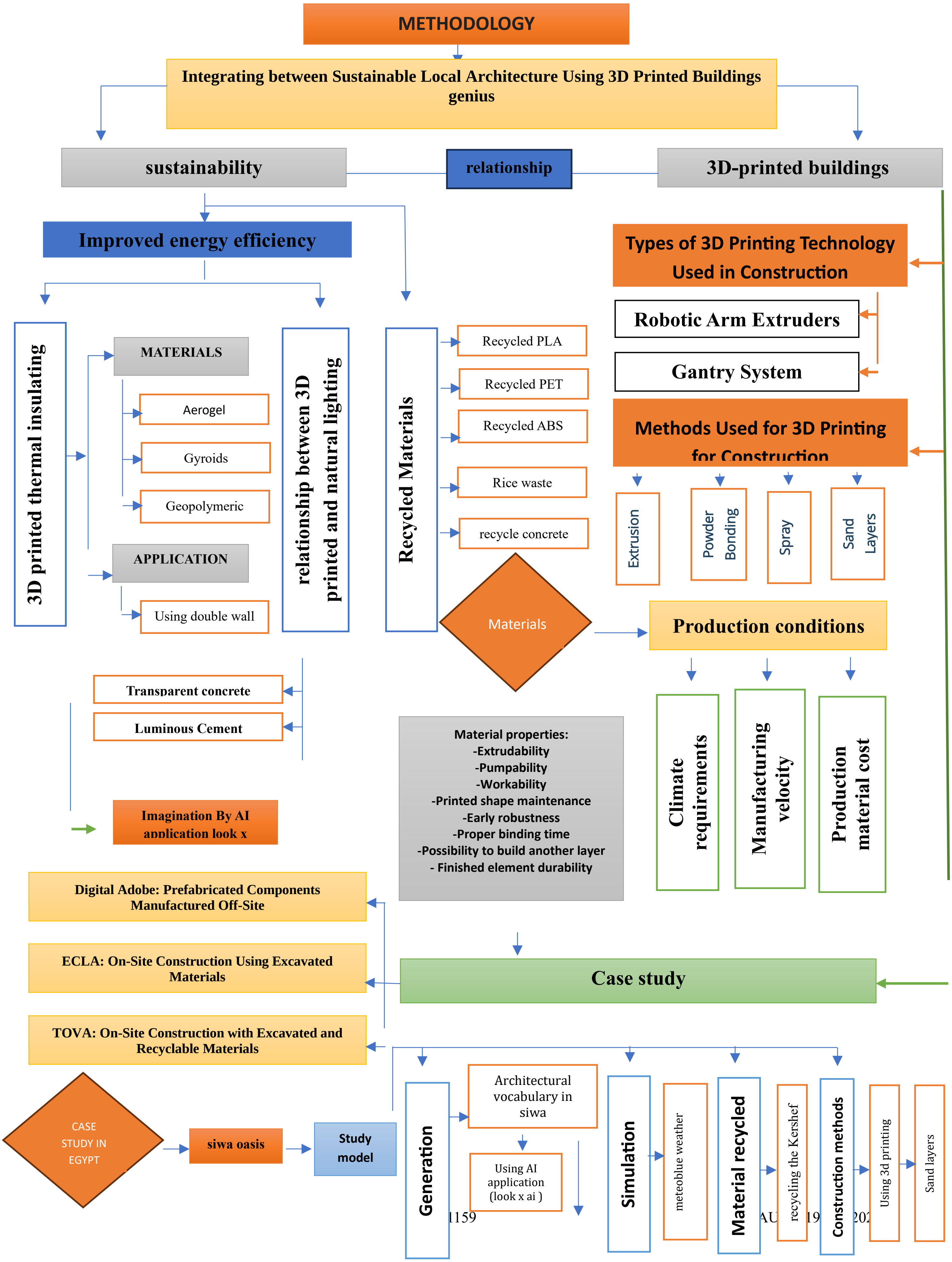
TOVA is the first architectural construction in Spain located in the facilities of Valldaura Labs, Barcelona, the construction process of TOVA incorporates 3D printing technology using a Crane WASP modular printer. Sustainable and locally sourced materials are utilized to minimize the environmental impact. The proximity of the materials within a 50-meter radius reduces transportation emissions and waste generation during construction.

The circular design approach employed in TOVA focuses on using reusable biomaterials throughout the construction phases. This includes a geopolymer foundation, a framework constructed from local earth mixed with additives and enzymes for structural integrity, a locally sourced timber roof structure, and wooden carpentry [24] shown on **Fig. 12.**

Fig. 12. TOVA project source [24]

8- METHODOLOGY TO ENHANCE SUSTAINABLE LOCAL ARCHITECTURE USING 3D PRINTED BUILDINGS WITH RECYCLABLE MATERIALS: shown on Fig. 13.

Towards an Applied Scientific Methodology to Enhance Sustainable Local Architecture Using 3D Printed Buildings with Recyclable Materials



Using grasshopper

fig. 13. methodology to enhance sustainable local architecture using 3d printed buildings with recyclable materials source researcher):

9-1 DESIGN Approach:

Builders in the Siwa oasis employ vernacular construction techniques, specifically the utilization of "Karshif" and mud, in the construction of their dwellings. The roofing system typically comprises palm wood and mud bricks. The architectural layout commonly includes a courtyard, which is a well-established and highly regarded design feature in hot-arid regions. Atriums are incorporated within the interior spaces of the houses, and the rooms that directly access the courtyard are designed to provide protection against the intense summer heat, the harsh winter cold, as well as the adverse effects of wind, storms, and sand in desert areas. **shown on Fig. 14.**

Fig. 14. explains construction methods in Siwa Oasis source [25]

9-2 study model using ai application :

Fig. 15. study model using ai application source researcher

Using LOOKX AI : Code: A residential building printed in clay and "Karshif" using a 3D printer in Siwa. The building is in the shape of a box, has windows and doors, and has wood and a modern architectural .

9-3 STUDYING THE CONCEPT OF FACADES:

Palm fronds are a common building material in the Siwa oasis region. Palm fronds are used in constructing roofs of houses and other structures in the area. The palm fronds are collected and dried before being used in construction. They are carefully and intricately installed to form a sturdy and weather-resistant surface. Palm fronds are considered abundant building resources in Siwa, reflecting the local building traditions and culture in the region. **shown on Fig. 16.**

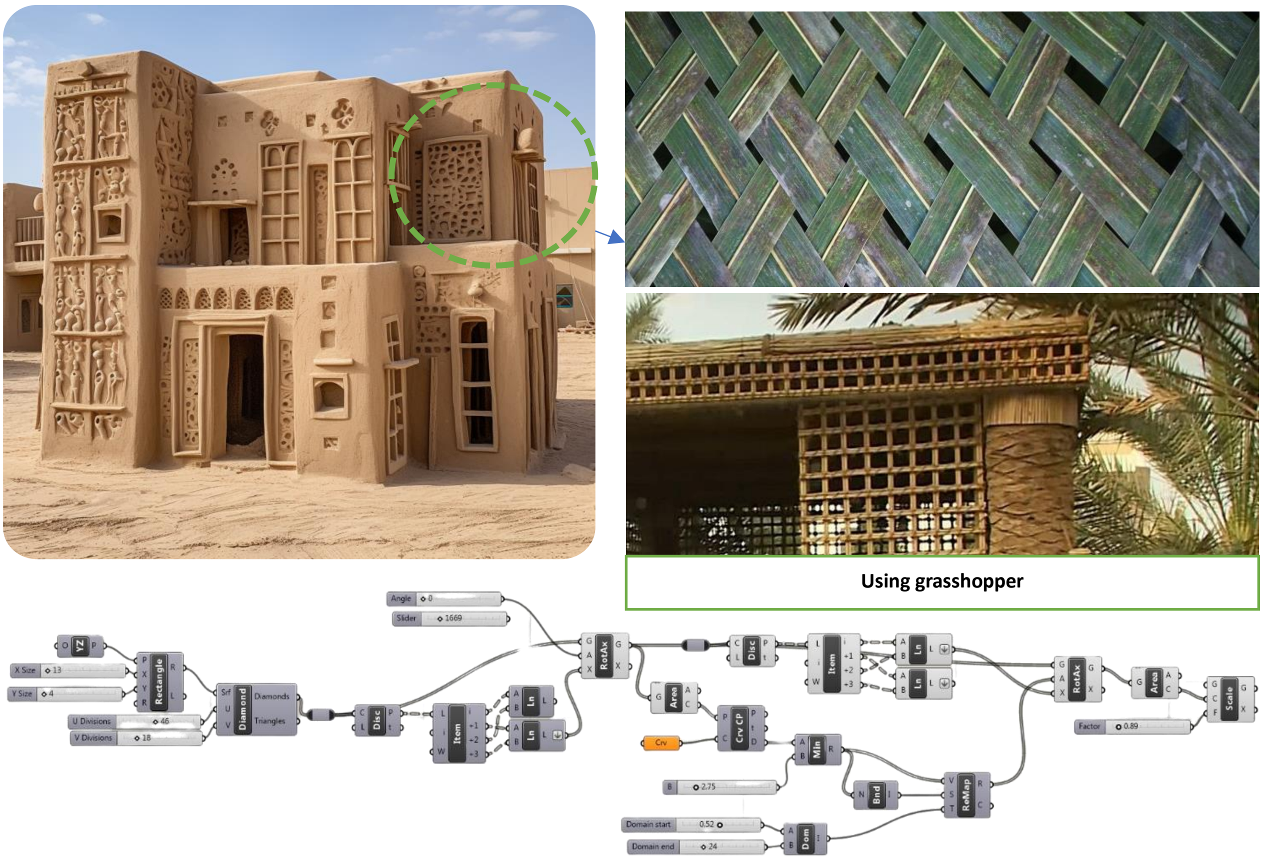
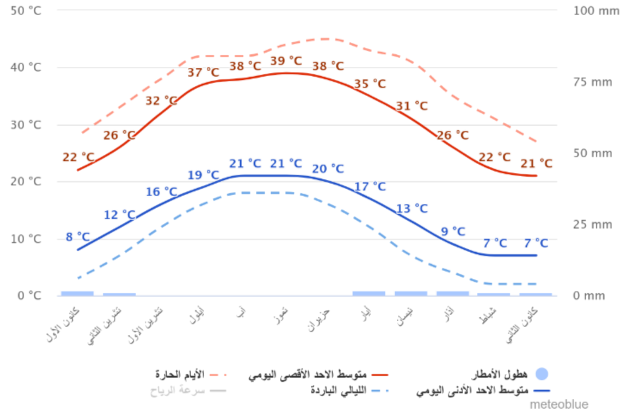
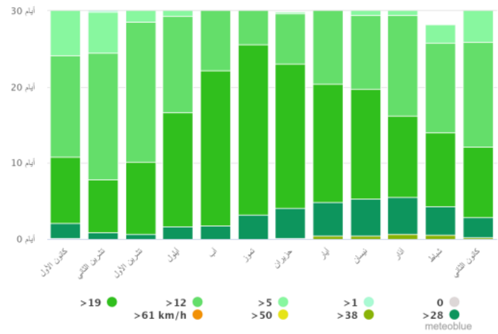


Fig. 16. Studying the concept of facades by grasshopper source: researcher

9-4 STUDYING THE Climate In Siwa :





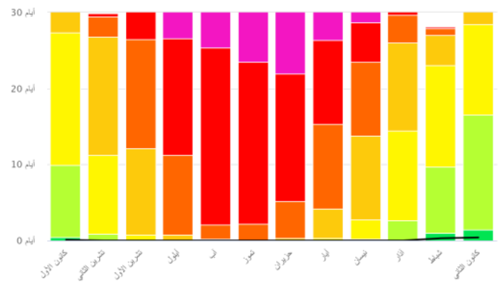


Fig. 17. Studying the Climate source [26]

9-5 STUDYING THE recycled materials used :

The primary building material used in Siwa is called "Kershef," and it is recycled. Kershef is a local material that is available in the Siwa Oasis as well as other areas in Egypt and some Arab countries. It is composed of a mixture of straw, clay, crushed stone, and sand. This material is considered sustainable and environmentally friendly.

9-5-1 The stages of recycling The Kershef material :

Fig.(19) Studying the concept of facades source: researcher

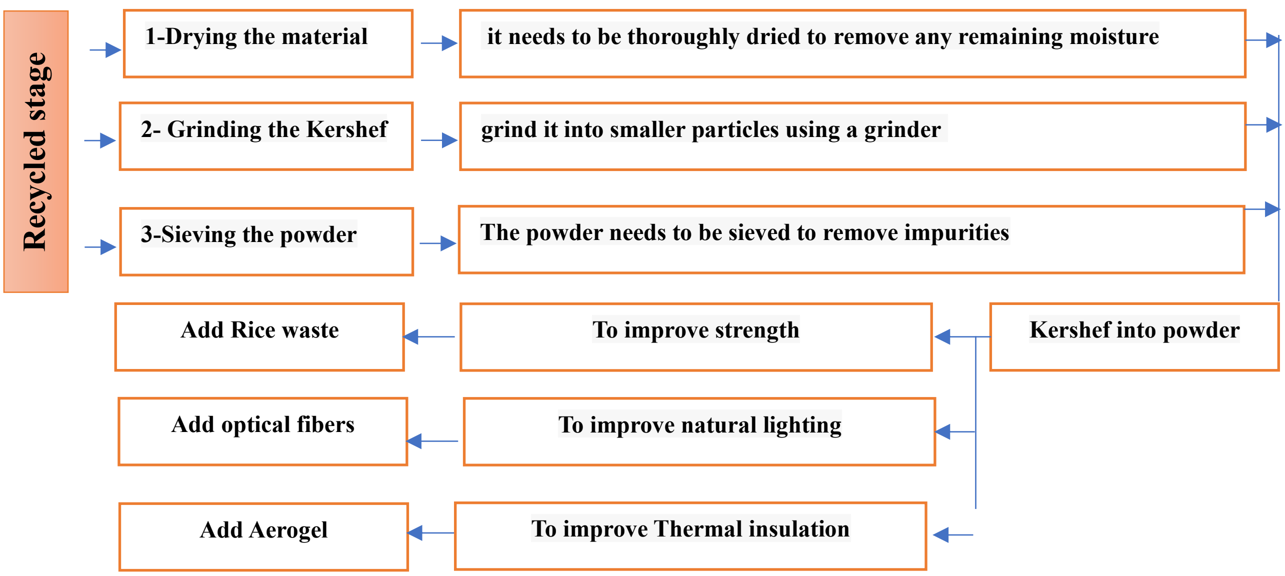


Fig. 18. The stages of recycling the Kershef material source researcher

10- Results EXPERIMENTAL METHOD:

The findings of this study demonstrate the significant potential of utilizing recycled materials in building construction to enhance thermal properties and enable energy conservation. By strategically incorporating materials such as Kershef, rice waste, and aerogel, the thermal resistance and overall thermal insulation value of building walls can be optimized, leading to substantial energy savings and environmental benefits.

- The calculations presented in this work provide a robust framework for assessing the thermal performance of building walls. The thermal resistance (R) can be determined using the equation $R = \Delta x / (k * A)$, where Δx represents the material thickness, k denotes the thermal conductivity, and A is the cross-sectional area. Subsequently, the overall thermal insulation value (U) can be calculated as the inverse of the total thermal resistance (R_{total}). The comparative analysis of the three recycled materials highlights their distinct thermal properties. Kershef, with a thermal conductivity of 0.05 W/m^2-K, exhibits the highest thermal resistance, followed by aerogel at 0.015 W/m^2-K and rice waste at 0.1 W/m^2-K. By strategically combining these materials in the wall assembly, the total thermal resistance can be optimized, leading to a reduction in the overall thermal insulation value.
- The implications of this study extend beyond the immediate energy savings. The use of recycled materials not only contributes to improved thermal performance but also aligns with the principles of sustainable construction, reducing waste and promoting a circular economy. Furthermore, the decreased wall thickness, from the commonly used 50 cm to 38 cm, can lead to additional benefits, such as increased usable floor space and potential cost savings in construction.

CONCLUSIONS AND RECOMMENDATIONS:

The findings of this research underscore the critical importance of leveraging an understanding of the available building materials on a given project site and maximizing the benefits of these materials through a comprehensive appreciation of their inherent nature, properties, recycling potential, and the strategic integration of modern construction technologies such as 3D printing.

The key findings of the research paper can be summarized as follows:

1- Implementing 3D printing technology empowers architects to enhance the sense of place identity and preserve local sustainable architectural traditions by utilizing the same indigenous building materials and architectural vernacular. This approach reinforces a strong connection to the site's cultural and environmental context.

2- Enhancing environmental conservation and optimizing the utilization of resources can be achieved through the recycling of existing materials and the strategic improvement of their structural and thermal performance characteristics. This holistic material management strategy promotes sustainability and reduces the carbon footprint of construction projects.

3- The incorporation of innovative materials, such as light-transmitting fibers, into the construction process enables the increased utilization of natural resources like daylight. This approach results in energy-efficient designs that further contribute to the overall sustainability of the built environment.

4- The adoption of construction technologies like 3D printing allows architects to strike a balance between the functional requirements of a building and its aesthetic qualities, while also facilitating the production of high-quality structures in a faster and more energy-efficient manner. This is achieved through the comprehensive analysis of building data and the creation of design models that thoughtfully consider site-specific and environmental factors.

To build upon these conclusions, future research should explore the following additional recommendations:

1- Investigate the life cycle assessment and embodied carbon analysis of 3D-printed building materials to further optimize their environmental impact.

2- Develop integrated design workflows that seamlessly combine 3D printing technology with Building Information Modeling (BIM) to enhance design coordination and construction efficiency.

3- Explore the integration of generative design algorithms and artificial intelligence to automate the optimization of 3D-printed building forms and material usage.

4- Conduct in-depth case studies on the successful implementation of 3D printing in diverse cultural and climatic contexts to establish best practices and lessons learned.

5- Assess the economic viability and scalability of 3D printing in construction to promote wider industry adoption and accessibility.

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