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Exploring a New Approach to Sustainable Building Construction using Agro Waste Materials

Rand J. Farhat[1], Ibtihal Y. El-Bastawissi[2], Ashraf Mansour[3], Maged Yousef[4]

[1]PhD Candidate, Faculty of Architecture: Design & Built Environment, Beirut Arab University, Lebanon
[2]Professor of Architecture Urban Design and Planning, Department of Architectural Engineering, Alexandria University, Egypt
[3]Professor of Architecture, Central Asian University, Tashkent, Uzbekistan
[4]Associate Professor in Architecture, Faculty of Architecture: Design & Built Environment, Beirut Arab University, Lebanon
Email: randfarhat7@gmail.com

With the rise of concern regarding resource depletion, environmental impact and waste production, the theoretical concept of expanding service life of goods and redeeming them into a circular economy came to light. Agro waste has gained much attention because of the tremendous amount produced globally. The destiny of such waste is either landfilling, indiscriminate burning, composting or biological transformation. Such disposal scenarios result in toxic emissions and thus with environmental implications. On the other hand, valorising and upcycling is said to result in materials and products with lower health risks because of the lower CO2 content and lower toxic emissions. This review focuses on the use of agro waste in construction material since its origins in ancient architecture till the latest findings. Through this review, the research aims to explore new approaches in upcycling agro waste into sustainable construction material. By analysing and comparing various examples and case studies where architectural spaces were constructed using materials manufactured / modified by agro waste, it is noticed such material rarely scale-up to industrial level, and constructed spaces are usually temporary or pilot studies with one or two floors. The research concludes that the agro waste to be used is best utilized within the same region of cultivation and proposes the use of transformed manufacturing, undergoing chemical and mechanical treatment, for higher performance, permanent and unlimited architectural spaces.

Keywords: Agro-waste Materials, Sustainability, Building Construction.

1. Introduction

Since 1970s, and with the rise of concern regarding resource depletion, environmental impact and waste production, the theoretical concept of expanding service life of goods and redeeming them into a circular economy came to light (Hebel et al., 2014). The utilization of waste into the economic cycle as a potential material is not new. Today, scholars investigate waste produced as a treasure.

As the construction industry dominates raw material consumption with 40% (Carra, 2017), it was pictured as a potential market to utilize waste. One approach is the use of organic waste. But why organic waste? It is well known that organic materials have lower CO2 content, lower toxic emissions and thus lower health risks. With an average of 0.6 BT organic solid waste being produced globally every year (MacArthur, 2017), utilizing organic waste in construction material initiates new opportunities for healthier, more environmental and less costly solutions.

Improper landfilling, indiscriminate burning or recovery composting or biological transformation is the destiny of 998 billion tons of agro waste (Agamuth, 2009). Landfilling can result in the emission of gases such as ammonia, carbon dioxide, hydrogen sulphide, methane, and nitrous oxide (Ugwouke et al., 2018). Incineration on the other hand produces climate-relevant emissions with environmental implications (Adejumo & Adebiji, 2020).

In this sense, the research aims to "to propose a new approach to integrate agro waste with construction materials for enhanced sustainability performance". To fulfil this aim, the paper looks through the literature of utilizing agro waste in the construction industry. Then, it analytically compares live examples of construction material used in constructed buildings' materials through history and in the modern era.

The research follows the qualitative approach. It utilizes the inductive methodology will be used to gather information concerning previous attempts in valorisation of agro-industrial waste in construction material through an in-depth desk study of reference books, peer reviewed journal articles, published research… Then, the comparative analytical methodology will be used to assess and compare different applied material in real life examples. Finally, the deductive methodology will be used to draw conclusions and propose a new approach.

2. LITERATURE REVIEW

The use of ago-waste is not novel. Ancient civilizations were agricultural; What came from nature was nearly their only resource. This review tackles the definition, sources and utilization of agro waste in industries and mainly the construction industry.

A. Definition of Agro Waste

Agro waste can include harvesting byproducts, or field residues, such stems, straws, stems, stalks, husks, leaves or shells, or cleaning and processing waste such as peels, pulps, seeds and stubbles (Madeira et al., 2017; Venil et al., 2020a). It rarely contains non-plant materials such as feathers or whey. This is usually biodegradable and/or recyclable.

Sadh et al. (2018) classified the recyclable agro-industrial waste into two main categories based on their source: the agricultural residues from harvesting or processing and the industrial residues.

B. Utility of Agro Waste in Industry

The most common utility of agro waste is composting it into bio-organic fertilizers. Another use is biofuels through incineration. Agro waste can also undergo fermentation to manufacture enzymes, flavors and fragrance. Also, it is usually incorporated in pharmaceuticals, dietary fiber, adsorbents, pigments, colorants and pH indicators (Mahongnao, Sharma, &Nanda, 2023). Another utility is transforming them into animal feed, antioxidants, and some chemicals (Sadh, P.K., Duhan, S. & Duhan, 2018).

C. Impact of Agro Waste on Environment

Even though agro waste is biodegradable, it imposes negative effect on the environment if left unhandled (Adebayo, 2018). The biodegradation of agro waste can take several months. Because of its high content of water, this process involves certain types of bacteria and amounts of microbes, increasing the risk of disease transfer and being pathogen to human, animals and plants (Soobhany, 2018). During fermentation, greenhouse gases such as methane are emitted, resulting in air and soil pollution (Qi et al. 2020; Wang et al. 2020). Additionally, these processes result in bad odors and visual pollution.

D. Agro Waste in Architecture

Even though the use of agro waste in construction is not a novel idea, yet there was no consensus on when it was first used. The following discusses the use of agro waste in the construction industry since ancient civilizations.

Agro Waste and Recycling

Organic waste management worldwide is classified among three scenarios: recovery, incineration, and landfilling (Lacoste & Chalmin, 2006 & Madrid el al. 2018). There is no precise data on where the agro waste produced goes, mainly because of the lack of data coming from developing countries. Yet, research has estimated that only 11% of the produced waste goes to modern incineration, 19% go to composting and the other fraction either go to landfills or is burnt in field (Kaza et al., 2018).

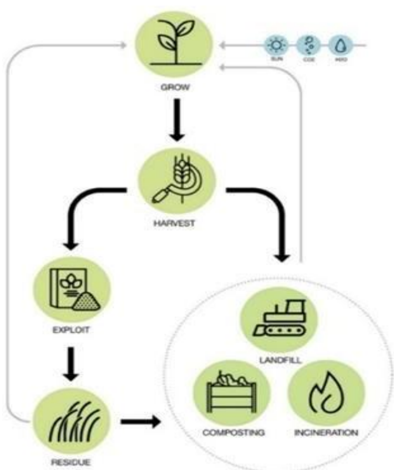

Figure 1 Current and Alternative scenario of Agro-Waste Management (source: Carra, 2017)

Landfilling can result in the emission of gases such as ammonia, carbon dioxide, hydrogen sulfide, methane, and nitrous oxide (Ugwouke et al., 2018). Landfilling and composting are proven to promote pollution problems mostly in developing countries (Figaredo, 2018); Composting, incineration and landfilling are found to contribute to 0.15, 2.15 and 2.75 kgCO2eq/kg respectively based on SimaPro Software database (Carra,2017). On the other hand, incineration utilizes agro-waste in a waste-to-energy scenario for managing waste yet producing by-products in the form of ashes that in return imply an environmental problem in disposal (Nguyen et al., 2019). Over 9% of the global energy production refers to incineration as indicated in the International Energy Agency statistical report in 2015. The tremendous number of ashes is also thought of as a potential material to be returned to the circular economy (Adejumo & Adebiji, 2020).

Figure 2 Agro Waste improper landfilling (photos from Arup Report, 2017)

Theory of Cradle to Cradle

Opposing the linear economy, or what is so called cradle to grave paradigm, William Andrews McDonough and Michael Braungart developed in the 1990s the concept of cradle to cradle, the circular economy (Mohjan, 2021). To them, it's no longer about generating 'less waste', but 'more good', that is to reclaim the waste as raw material again and putting it into the chain. This philosophy was analyzed by many researchers. In his review, Mohajan summarizes the three principles: waste equals food (waste of one action should be the raw material of another), use current solar income (that is renewable energy), and celebrate diversity.

Origins of Waste in Architecture

The use of dried straw and husk with mud bricks for example was recorder to date to the Mesopotamia around 4000 B.C. (Pumpelly,1908) or even older (Mink,2012; Berge, 2009). Other reviews document the ancient Egyptian civilization to be the first to use natural fiber reinforcement for mud bricks (Maher & Madrigal,2021). That is due to their geographic settlement beside rivers, which allowed the cultivation of crops.

Neighboring them, specifically in the Arab Peninsula, the use of palm fronds and stems was known as the Arish architecture (Hobbs,2017). It wasn't until the discovery of oil in the late 1900's that they've been nomadic (Heard-Bey,2009), during which they could build out of palm only; the tall trunks were used as columns and beams, while the fronds and leaves were used as envelopes. Leafless fronds were grouped into fences and window meshes known as mashrabiya screens (Piesik, 2012; Duncan & Tomic, 2013).

Figure 4 Arish Architecture in the Arabian Peninsula a: Buraimi Oasis, April 1948 (source: Arish: Palm-Leaf Architecture, Piesik, 2012) b: Reconstruction of arish home with wind-tower, Dubai Museum (source: Heritage In The Lived Environment Of The United Arab Emirates And The Gulf Region, Hobbs, 2017)

After that, the agricultural era dominated until the industrial revolution in the 18th Century (Lu, 2016). The availability of natural resources played a great role in material selection, while the climatic condition and human behavior inspired the techniques (Galantay, 1987). Allied, the vernacular architecture stands as a proof of how societies have utilized what ever they harvested into shelters; palm roofs weaved on vines are highly used in Amazonian zones such as Ecuador, dried grass and stacks form the "beehive" Zulu homes of South Africa, local stacks and straws of different colors and sizes overhang the roofs of Wenohian dwellings in Ghana (Piesik,2017).

Figure 5 Examples of Vernacular Architecture Utilizing left overs of local Agriculture in Construction (a: palm and vine weaved roof, Ecuador - b: dried grass and stack beehive structure, South Africa - c: stack and straw roof, Ghana (source: Habitat: Vernacular Architecture for a Changing Planet, Piesik, 2017)

Potentials of Using Agro Waste in Building Construction

However, the progression of technology and the rapid increase in population imposed the need to new techniques and approaches in construction. Coupled with that, the industrial revolution significantly increased the variety of material and new products, causing a change in the pattern of material usage (Mohajan,2019). Later, the raise of awareness on the environmental impact of construction industry accentuated the need for better performing materials and techniques (Hebel et al., 2014).

In his keynote presentation at the Research Symposium on the Development Strategy for Innovation Design, Yongxiang Lu (2016) identified three eras of civilization: the agricultural era, the industrial era, and the knowledge era. According to his him, the material design paradigms of the knowledge era are focused on sustainable and eco-friendly approaches to design super green materials. It is the era of nanostructures, low dimension material, and the return to utilizing more natural material (Lu,2016).

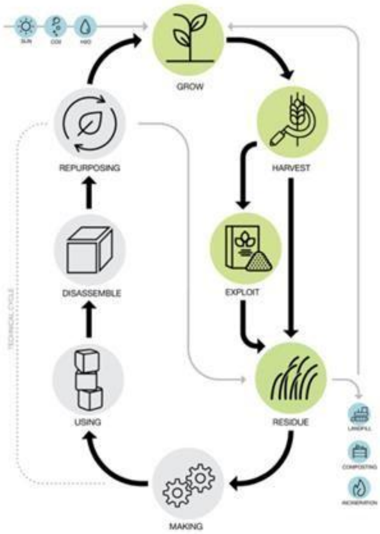

Figure 6 Alternative Model: technical exploitation of agro waste (source: Carra, 2017)

Indeed, the past decade has witnessed a significant focus on circular economy in the research on building and construction industry (Norouzi et al., 2021). A big share of which was concerned with naturally derived material and agricultural waste.

In 2014, David Benjamin of New York Architects, The Think, implemented the first mushroom brick, made up of corn stalks in a structure designed to serve as shading, seating and gathering at MoMA's Warm Up music festival, New York (Stott,2014).

Later in 2015, Arup, GXN Innovation and several other partners design a self-supporting bio-composite façade made up of natural fibers coming from crops waste as flax, hemp and jute, bonded with resin manufactured form sugar cane and corn harvesting residue. The system was able to achieve U < 0.8 W/m2K, and was reported to reduce up to 50% of the embodied energy (Stott,2015).

Since then, leading material manufacturers-initiated research in this field, many of which are now in market. For example, CaraGreen, architectural material manufacturers, have put in market a group of environmentally certified material made up of agro waste. Their focus was on MDF boards made of reclaimed sorghum stalks boards or wheat straw board, and decorative panels used as interior finishes involving a variety of alpine hay and flower petals (Lucas, 2019). Biohm, a research and development firm in the field of bio manufacturing, is another example of innovative utilization of agro waste. They put in market bio composite made up of coffee chaff and orange peel (Maheshwari, 2021).

Furthermore, leading young architects are now adopting the approach and researching its possibilities. At Dutch Design Week, 2019, explored the KAIKU Living Color system, aiming to utilize agro waste residue from avocado, pomegranate and onions to create an alternative pigment to petroleum-based colors (Doshi, 2019).

In 2021, it hosted ShowHome, a model house designed by Eco-design studio Biobased Creations, using over 100 plant-based materials derived from wood, mycelium, seaweed, straw and vegetable fibers. It included 3D printed wall panels made up of sewage residue, interior wall panels from mycelium, furniture from eggs and oyster shells, straw exterior cladding and several other recycled materials of rubber and metal (Frearson, 2021).

In 2023, Dubai Design Week hosted a group of innovative material; TECOM Group PJSC presented bioplastic sheets from orange residue, EDGE Architects crafted the 'EDGE MORPH' from boards derived from palm fronds, and so did Tash architects who also used palm to build their shading canopy. Similarly, Mitsubishi Jisho Design built the 'Arabi-An' made from tea grains and grapes.

Reem Jeghel presented palm veneer, while ARDH Collective presented vegan leather from date seeds. Aya Moug presented multi-use material moldable from papyrus plants and many others (Bedirian, 2023).

Additionally, academic research in this field is showing much interest. The two researchers Kota Machida and Yuya Sakaki at Tokyo University developed a technique to create cement from agro waste by compressing pulverized dried particles (Tanaka,2022). Yet, there is still a limitation. According to Laura Ferguson, it is already known that natural materials have the potential, yet the issue remains in how it is integrated by architects and designers buildings. Moreover, the production approaches are still relatively expensive if compared with conventional construction material (Baratto, 2022).

Classification of Manufacturing Methods

Throughout literature, repurpose organic waste in the construction industry has been classified based on two main aspects; ways of assembly and/or manufacturing (Hebel et al., 2014), and final usage of the material (Maraveas, 2020). To start with, Hebel, Wisniewska and Heisel highlighted the recovery of waste material in the construction industry in a book in 2014. In their book, Hebel et al. classify ways of utilizing waste into architecture under five main categories:

o Densified waste: They are products resulting from the compression of loose waste material into denser matter, with reduced volume and higher state material. A good example is turning straw waste to panel boards. Upon pressure, the starch in straw is activated and acts as self-binding agent. Strawtec Building Solutions, Germany was one of the leading companies that, with corporation of many architects and researchers implemented this strategy in assembling Sustainable Emerging City Units (SECU).

o Reconfigured waste: They are materials result from mechanical processing of the waste material (shredding, breaking, sawing, grinding…) into smaller matter (pellets, chips, strands, fibers…) added to an organic or inorganic matrix as an adhesive. Almost every agro waste is a valid raw material for this method. These boards are widely used in furniture and in interiors.

o Transformed waste: These are materials that result from waste material alteration in the presence of other material, such as chemical treatment. Nano-treatment, foaming and many other methods are being investigated nowadays.

o Designed waste material: They are products that were originally manufactured to maintain their physical form and material composition while changing the function. Sascha Peters described organic waste as to be the future of designed waste products; she pictures the idea of utilizing agro-waste in new material a designed waste material approach (Sascha, 2018).

o Cultivated waste material: Cultivation is a concept based on the growth of microelements in a biological action. This is mainly the mycelium blocks cultivated from agro waste.

Previous Readings on using Agro-Waste in Building Construction

Indeed, the past decade has witnessed a tremendous amount of research concerned with repurposing agro-waste in several fields, one of which is the construction industry.

Uses in Bricks

Earth is one of the oldest materials used in construction (Minke, 2006). Before compression emerged, natural fibers were added to earth material. Yet, in 1985, Regassi suspected the compatibility of fibers with the compression process (Gontijo, 2020). And since then, studies began concerning the addition of abandoned fibers into CEBs. The latest was experimented by Gontijo, School of Technology and Management of Bragança. Gontijo added inert dry municipal organic waste into the mixture of sand, kaolin, cement, and water. As a result, thermal conductivity was reduced up to 22.2%, thus reducing heat transfer through the building envelope, without affecting the chemical behavior. Fire performance was also found to be satisfying (Gontijo, 2020).

Other studies focused on the use of single agro-waste material as an additive with various percentages to clay weight. Different amounts of rice husk ashes and sugarcane bagasse ashes proved to improve the buildings' environmental performance due to increased porosity with an optimum of 5% of ashes to clay weight as stated by Kazmi (2016). The produced bricks were lighter in weight and thus forced less load on the building's structure. Increased percentages of ashes were observed to decrease tragically the physical strength of bricks (Kazmi, 2016). Similar results were discussed by Kizinievic (2018) and Taurino (2017) while incorporating oat and barely husk, wine waste, and empty fruit bunch with clay respectively. De Silva and Perera went further in studying rice husk ash (2019) and experimented the acoustical performance. Improvement in compressive strength and water absorption were noticed in addition to 6°C reduction in indoor temperature and 10dB reduced noise at a percentage of 4% of incorporated agro-waste to clay weight (De Sliva & Perera, 2019).

Uses with Cement

Furthermore, concrete being one of the most used building materials in the modern era is made up of cement, aggregates and water (Prusty et al., 2016). Research focused on finding the compatible substitute for both cement and aggregates in a manner that doesn't affect the chemical bonding and hardening process of cement. Such practices were described by Maraveas (2020) as green concrete.

Ashes are known for their pozzolanic nature in general. Research in Pakistan, where sugarcane is plentiful, experimented the use of sugarcane bagasse ashes SCBA as a partial substitute for cement in M15 and M20 concrete mixtures. Specimens were cast and cured for 7, 14, and 28 days. The average compressive strength was the highest on all time intervals for 5% SCBA for both M15 and M20 concrete mixtures. Moreover, the average compressive strength for 10% SCBA replacement was higher than 0% and less than 5% SCBA (Sajjad et al., 2017). Sugarcane bagasse ashes were also examined as a substitute for aggregates as well; Modani and Vyawahare experimented 0%, 10%, 20%, and 30% aggregate replacement by SCBA and similar results in the compressive strength were stated. 10% SCBA replacement was the optimal (Modani & Vyawahare, 2016).

A further study introduced bamboo ashes BA as a second additive to test the pozzolanic aspects of the mixture. In addition to the mechanical properties, Rodier et al. analyzed the X-ray diffraction, isothermal calorimetry as well as the thermal gravimetric results. The findings stated that SCBA and BA mixture had a higher pozzolanic activity than SCBA alone (Rodier et al., 2019). Moreover, SCBA was investigated for its compatibility with self-compressing concrete to be used as a viscosity-modifying agent by Akram et al. (2009). The examined mixture has found to be comparable to the control mixture with 35.63% reduced cost (Akram et al., 2009).

Other materials can also be compatible with cement. For example, ground nut shells were found to be a good replacement for fine aggregates with less density but reduced mechanical properties (Kimeng et al., 2015). Such additions are recommended in non-bearing partitions. The same test was performed by Sada et al. for reinforced concrete slab, and only 5% replacement of fine aggregates was stated as optimal (Sada et al., 2013).

A leading researcher in the field of material innovation is Mohamed Saafi, Lancaster University, UK. His recent research tackled the incorporation of nano-platelets extracted from sugar beet roots and carrots as cementitious material in 2019 and 2020 respectively. In partnership with Cellucomp Ltd, a leading manufacturer in sustainable material, studies began on using sugar beet root in the form of 2D nano-platelets in concrete mixtures. These nano-platelets were characterized by their hydrophilic action, dispersion in water as well as high specific area (Hasan et al., 2019). The addition of 0.2wt% of sugar beet root nano-platelets was concluded as optimum; 75% increase in flexural strength, 200% improved modulus of elasticity, 88% more fracture energy, and 106% increased fracture toughness (Hasan et al., 2019). The following experiment suggested the addition of carrot residue nano-platelets into the concrete mixture. Similar results were observed with less influence; 23.2% increase in compressive strength compared to 75% with sugar beet root (Chi et al., 2020).

Frankly, the nano-platelet form of sugar beet root was not the only attempt to use this waste as a cementitious material; Gharieb and Rashad (2020) experimented carbonation lime residue CLR to substitute cement in concrete mixtures. Different ratios were tested, and 5% replacement of cement with sugar beetroot CLR was stated as optimum with improved compressive strength and enhanced microstructure (Gharieb & Rashad, 2020).

In the same sense, the need to lighten cement panels as profitable interior partitions in industrial buildings derived the study of incorporating jute waste in particle form to cement in the presence of starch. Ferrandez-García et al. stated that 5-10% of waste jute particles to cement weight can result in improved modulus of rupture, moulus of elasticity as well as better internal bonding and thermal conductivity. Such boards are suitable for interior partitions, dropped ceilings and maybe flooring. Additions of jute waste above this percentage reduced the mechanical properties and limits the use to insulation panels (Ferrandez-García et al., 2020).

Uses in Particleboard

Research tackling particleboards is abundant either to investigate particle substitutes or the used adhesives. Conventionally, petroleum-based adhesives such as urea formaldehyde dominated this industry. Formaldehyde resins were proven as a carcinogenic material, causing health problems like eye irritation and respiratory problems (IARC, 2012). On the other hand, ood particles consumption stress on forest resources leading to deforestation (Adediran et al., 2019).

Several ago-waste materials have been utilized and tested as partial or complete substitute in particleboard production. Maize cobs in the form of powder was experimented with epoxy resin as adhesive. The proportions of maize cob and resin tested were 40:60, 50:50, and 60:40. A hardener was used to facilitate the drying and toughening of epoxy resin. As a result, the 60% maize cob didn't have comparable compressive and tensile strengths to the other two specimens, which in turn were found to be feasible and functional as tabletops, insulations boards, interior partitions, ceilings, and furniture applications (Nayaka, 2020).

Way before that, a study held in 2016 at the Center for Architecture, Science and Ecology at the Rensselaer Polytechnic Institute, USA, experimented coconut husk particles with bio-binders of renewable resource: pith, mycelium and soy. Pith was dried and mixed with e2e protein soy, then incubated with mycelium. After the growth period, the mixture was dried in open air. As a result, the manufactured boards were compatible to medium density wood-based boards in market (Lokko et al., 2016).

Another study experimented with the use of sweet sorghum bagasse with citric acid in the presence of sucrose in different percentages. The optimum ratio of citric acid and sucrose is 15:85 and 10:90; improved mechanical properties, thermal behavior, decay resistance, and lowered formaldehyde emission (Kusumah, 2017). Coconut husk particles were also examined as pine wood substitute for medium density particle boards and were concluded to be comparable to pine wood particles with no substitution (Narciso et al., 2020).

As for high density particleboard production, Sugahara et al. investigated the utilization of sugarcane bagasse with urea formaldehyde and PU-castor. Sugarcane bagasse best substitutes 40% of wood particles, and PU-castor concluded to be more efficient (Sugahara et al., 2019).

Targeting only particle substitution, a recent study experimented with waste from prunus avium, where particles were sorted based on dimension to be used as core of face layers. These particles were glued using urea formaldehyde and paraffinic emulsion as hydrophobic addition. After testing, it could be concluded that bards met minimum requirements of low-density particle boards and thus have the potential to be developed into useful material (Hernández et al., 2020).

Looking for a more complex solution, hybrid agro-waste particles were incorporated with known percentages: rice husk, eggshell, cassava peel and palm kernel shell. Different behaviors were noticed, but as a conclusion they were found to be useful in furniture and interior applications (Adediran et al., 2019).

Uses in Bio-polymers, Bio-adhesives and Foams

Utilizing agro-waste in the polymer industry can be seen in two categories: valorizing through biological processes to transform waste into biopolymers such as polyhydroxyalkanoates PHA, or as a reinforcing additive to organic or inorganic poly-matrices. Regarding the first category, one of the latest is a study performed in University of Toronto Scarborough by a group of graduates named Genecis, who transformed, through bacterial action, sugar beet root by-products to PHA filaments used in 3D printing (Campbell, 2018). Sugar beetroot water and molasses were also the focus of Zohri (2019). Yet, this is not the scope of the research.

For the other category, PU foams are characterized with their light weight in correspondence to their good mechanical, thermal, acoustic and water absorption properties (Kairyt˙e et al., 2020). Yet, its flammability was the biggest drawback which for years was treated with halogenated filler additives. In turn, such additives release toxic emissions upon firing. Organic agro-waste additives were proposed as compatible to PU foams for the lack of reactions and the minimal effect on viscosity (Rao, 2018). Waste ash of municipal organics was tested for 10-50% as additive to PU by Kairyt˙e et al. As a result, 30-50wt% addition gives comparable mechanical and physical properties, in addition to the advancement in flame retardant action (Kairyt˙e et al., 2020).

Suggested Parameters of Analysis

Based on what has been presented previously, agro waste in the shape of field residue has been used as material or material additives in the construction industry. With the industrial revolution, and along with the development of the food industry, new forms of integrating agro waste in the construction industry were introduced.

- Agro waste can be classified based on the method of treating it before integrating it with construction materials. It can be densified, reconfigured, transformed, designed and cultivated.
- Throughout history, the material used was selected not for its unique properties, but for its availability.
- They were used mainly as additives with particle boards and bricks, aggregate substitutes, with paints and as adhesives, covering a wide range of building components.

For so, the suggested parameters of analysis are as follows:

- Target for integrating waste materials with construction materials
- Building typology
- Location, climate and weather challenges considered
- Type of agro waste used as raw material to be added
- Application material by which the enhancement is applied to
- Building component(s) where the new material is used
- Method of manufacturing
- Specific requirements

- Key indicators monitored or tested
- Methods for testing

3. METHODOLOGY

The analytical and comparative analytical methodologies are used. The in-depth desk study is used to gather information from books, magazines, and product datasheets. The selected buildings are then analysed based on the concluded parameters in the previous part.

To perform the analytical comparative analysis, three projects were selected to be interpreted. These projects were selected based on the following criteria:

- Dating no longer than the past decade.
- Availability of data on the project.
- Existing projects.
- From various climatic locations.
- Buildings involve daily activity (not sculptural).
- Not temporary structures.

A. Agrocrete Manufacturing Unit, Roorkee, India, by Tarun Jami, 2019

In 2019, the Indian civil engineer Tarun Jami started his journey in testing and manufacturing Agrocrete building blocks. The bricks were carbon negative, with cost reduced to half and thermal insulation increased by fifty percent (Dsouza, 2022).

Typology:

The results of the tests showed the bricks performed well. To validate, Tarun used these bricks to build a load bearing structure, as an extension to his office in Roorkee. This built-up unit was later used as a manufacturing unit. The built area was 100 square meters per floor (Dsouza, 2022). The blocks were later used to build low-cost homes in India.

Figure 7 Agrocrete Manufacturing Unit Photo by: Tarun Jami

Climatic Conditions: Roorkee is known for its warm to hot weather all over the year. It's also known for having high levels of precipitation, especially in the summer.

Design Aims and Targets:

Few observations were the motives for Tarun Jami to start his company: the smog of vehicles that almost blocks the sight in Delhi, and the reported deteriorating air quality. Trauna started his mission of manufacturing carbon negative construction material (Wingify Foundation, 2022).

Integration of Agro Waste:

The agro waste used is a mix of farmers residue that is mechanically processed, dried and chopped. Later, it is mixed with a cementitious material, BINDR. This is also an upcycled material of the industrial waste of steel and paper industries. Its low carbon and the upcycled content make it an added value to the bricks (Dsouza, 2022).

Assessment of Used Materials:

To validate their approach, GreenJams performed life cycle assessment LCA with reference to the standards ISO 14020:2001, ISO 14025:2006, and EN 15804:2012+A2:2019. The LCA focused on Global Warming Potential, Ozone Depletion Potential, Acidification Potential, Eutrophication Potential, Photochemical Oxidants Creation Potential, Abiotic Depletion Potential, and Water Depletion Potential (GreenJams, 2022).

B. The Nest House, Roskilde, Denmark, by the Circular Lab, 2024

Pioneered by the Circular Lab at Roskilde Festival, 2024, the Nest House is biogenic housing prototype, made entirely from straw, clay and timber. Promoting healthier spaces for users and the environment by which the building exists, the project was more of scalable system used as a model for experimental purposes (Pylypchuk, 2024).

Figure 8 The Nest House (EFFEKT, 2024)

Typology:

The unit presented at the Roskilde Festival was a single room utilized with a kitchen corner. As mentioned, with its modular design approach, the unit is scalable, with the ability to expand in various directions to add more rooms to the house (Pylypchuk, 2024).

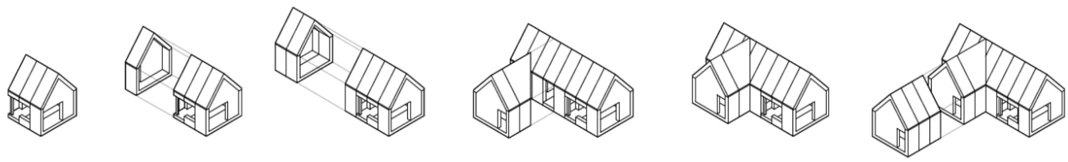

Figure 1 scalable schema proposed by the Circular Lab (Source: Pylypchuk, 2024)

Climatic Condition:

Designed for European usage, modulina straw panels are intended to resist cold weather. In Denmark, the climate has a consistent cold temperature, with high levels of precipitation over the year. With thermal conductivity of 0.059 W/mK, and thickness of 35-45cm, the panels should be able to maintain indoor air quality with little concern about the outdoor temperature (Marcinkus, 2024).

Design Aims and Targets:

The purpose of the design was to create a healthier space in the first place. Modulina Straw Panels, the manufacturers, thought the use of biogenic materials is healthier for both human and the planet. Their panels aim for enhanced thermal properties, less harm to the ecology upon manufacturing, better microclimate in terms of indoor air quality, and reduced sound and noise transmission.

On the other hand, the Circular Lab viewed the use of such material as to be resource conscious, respecting and preserving the environment by which it exists. It's also expected to reduce buildings' carbon footprint.

Integration of Agro Waste:

The panels produced by Modulina Straw Panels are made up of compressed straw. For the structure, upcycled timber is used. Straw is only densified without undergoing any major changes.

Assessment of Used Materials:

As a product, modulina panels are not certified, yet they are tested and claimed by the manufacturer to be sustainable, with high thermal insulation and structural strength sufficient to be used as load bearing or as non-load bearing panels. The panels are guaranteed for their fire resistance, high insulation and weather resilience (Marcinkus, 2024).

Based on the manufacturer's reports, the panels are characterized with -150 kgCO2e/m3 and minimal embodied energy when compared to masonry construction (Marcinkus, 2024).

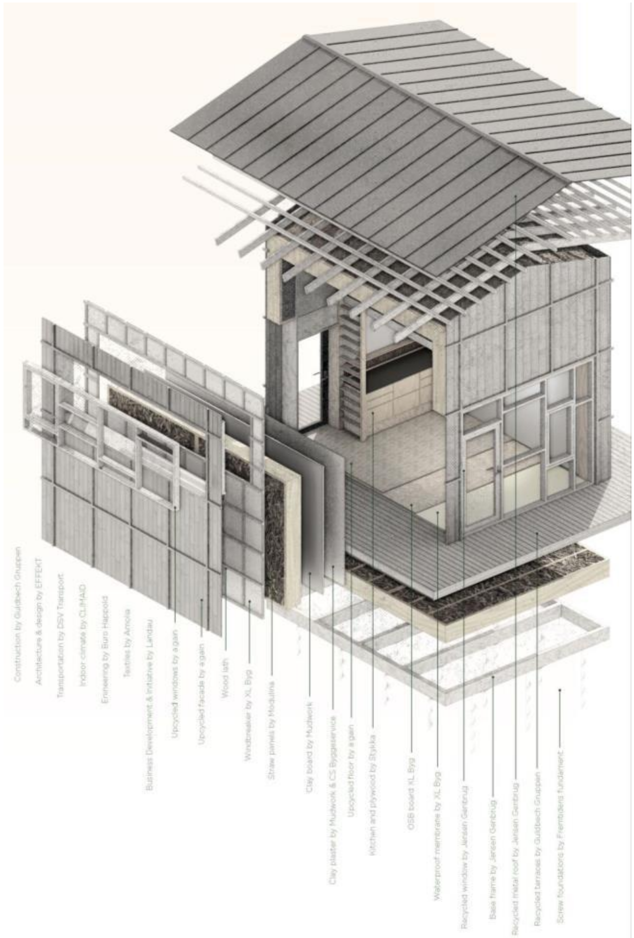

Figure 10 Material Analysis used in Nest House, Denmark (source: modulina.eu)

C. Discussion (Comparison)

It is worth saying that the search for implemented architectural projects using agro waste integrated materials or products was not a quick win. Very little count of materials and products are scaled up to manufacturing scale. Despite the unlimited number of materials the industry is overwhelmed with, it wasn't quite easy to identify a well-developed product upcycled from agro waste, being marketed and used by architects and designers.

The two projects analyzed are put into comparison with one another based on the criteria by which they were looked at.

Table 1 Comparison between the analyzed projects (source: author)

	Project 1 Agrocrete Manufacturing Unit, India	Project 2 Nest House, Denmark
Building typology	Workshop	Residential
Climate	Warm to Hot	Cold

Targets & Aims	Carbon negative	Healthier space Less harm to the ecology Resource consciousness
Agro waste	Farmers residue	Straw
Application	Building blocks	Compressed panels
Building component(s)	Walls	Exterior envelope (walls and roof panels)
Method of manufacturing	Reconfigured	Densified
Key indicators monitored or tested	Global Warming Potential Ozone Depletion Potential Acidification Potential Eutrophication Potential Photochemical Oxidants Creation Potential Abiotic Depletion Potential Water Depletion Potential	Thermal Insulation Structural Strength Fire Resistance Insulation Weather Resilient Embodied Energy CO_2 Emission
Methods for testing	LCA in reference to ISO 14020:2001, ISO 14025:2006, EN 15804:2012+A2:2019	Comparative analysis with conventional masonry work

4. CONCLUSIONS

Ago-waste, resulting from either field or industrial processing, has been widely valorized in the construction industry. Such practices are not limited to specific times in history, neither to a specific culture, or developmental status; from ancient civilizations to modern times, and from the third world countries to the most developed. Yet, the methods, techniques and raw materials are the variables.

The latest research tries to step with the practices into the market, focuses mainly on the exterior envelopes, as organic material has shown enhanced performance in isolation interior from the exterior factors, such as temperature, humidity, and acoustics.

The current practices are mostly focused on mechanical and/or chemical treatment of agro-waste. Indeed, literature shows potential in this method and mainly using nanomaterials. Yet, there is the gap between research and the industrial market.

On the other hand, raw material is noticed to be mainly related to the location. It's availability in high quantities is a main key in the application.

Based on what has been presented, the research proposes the need to address industrialization and the manufacturing of high-performance materials, through transformation of most available agro waste. This material is to be used to alter the conventional material used in construction, to make it easier to include it at an industrial level.

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