Publisher: Engineering College, Al Muthanna University Open Access

DOI:10.52113/3/eng/mjet/2026-14-04-/76-89, Vol. (14), Issue (4), (2026)

Muthanna Journal of Engineering and Technology
MJET

Submitted 24 May 2026, Accepted in revised form 18 August 2026, Published online 18 August 2026

Sustainable Circular Architecture: Drivers and Barriers in the Transition from Linear Construction – A Case Study of Bosco Verticale, Milan

Kais Abdulhusein Abbas

College of Architectural Engineering, University of Technology- Iraq
**author's E-mail: Kais.A.Abbas@uotechnology.edu.iq*

Abstract

The urgent environmental challenges of resource depletion, waste generation, and climate change necessitate a paradigm shift in architecture from the conventional linear "take-make-dispose" model toward a regenerative circular economy. This study seeks to analytically investigate the key drivers and barriers to implementing sustainable circular architecture, with a specific focus on high rise residential buildings. Employing a qualitative case study methodology, this research analyzed the design, implementation, and ecological performance of Bosco Verticale in Milan against established circularity principles and LEED certification standards. According to the study's results, Bosco Verticale exemplifies circularity because it combines biodiversity with many features, including: sequestration of 30 tons of CO_2; having more than 1,600 different species; features for reusing greywater; and the use of durable modular building materials. However, the study has identified many significant barriers to adopting these types of buildings more broadly: very high costs associated with construction; a need for intense, highly specialized maintenance; and structural complexity associated with each design. Moreover, it was found through the research that (BIM) and (AI) are two new technologies that may help reduce the roadblocks that have been encountered in the adoption of circular buildings. The result of this study is that the circular built environment can be adopted and implemented in an environmentally sustainable manner; however, it will take a concerted effort by architects, policymakers and urban designers to break down the legal, financial and social barriers that are preventing the sustainable construction of buildings with a circular design.

Keywords: Circular architecture, Circular economy, Durability, Recycling, Sustainability, Vegetation, Waste reduction.

1. Introduction

The classical linear economy architectural practice operates through one trajectory 'take-make-dispose'. Worldwide, this one-way process generates about 40% of all waste through extracting virgin materials, energy-intensive construction, and eventual demolition. It will result in less non-renewable resources, more carbon built into our products than ever before, and will destroy natural environments around the world with all the garbage sent to landfills and around 37% of the global greenhouse gas emission footprint [19].

Due to its inefficiency, it has exacerbated urban heat islands, accelerated biodiversity loss, and failed to adapt to pressures from changing climatic conditions. With a growing world population, resources are becoming harder and more costly to obtain (Fig. 1).

In contrast, the circular economy offers a new paradigm of construction as it focuses on creating a regenerative cycle of construction. The new cycle of construction emphasizes material reuse, modularity, and biodegradability. This will lead to a reduction in resource extraction and creation of waste, lower embodied carbon and increase ecological resilience. This paradigm shift is even more urgent now that by 2050, there will be nearly twice as much demand for raw materials as there is today; therefore, this will create enormous stress on our already stressed, overloaded ecosystems [11].

The history of ecological integration into architecture is not new; one of the earliest examples of utilizing landscaping and ecological systems within human constructed spaces is the hanging gardens of Babylon, and as such is the early initiation of a long-standing practice of utilizing bio-integrative techniques within building structures [3].

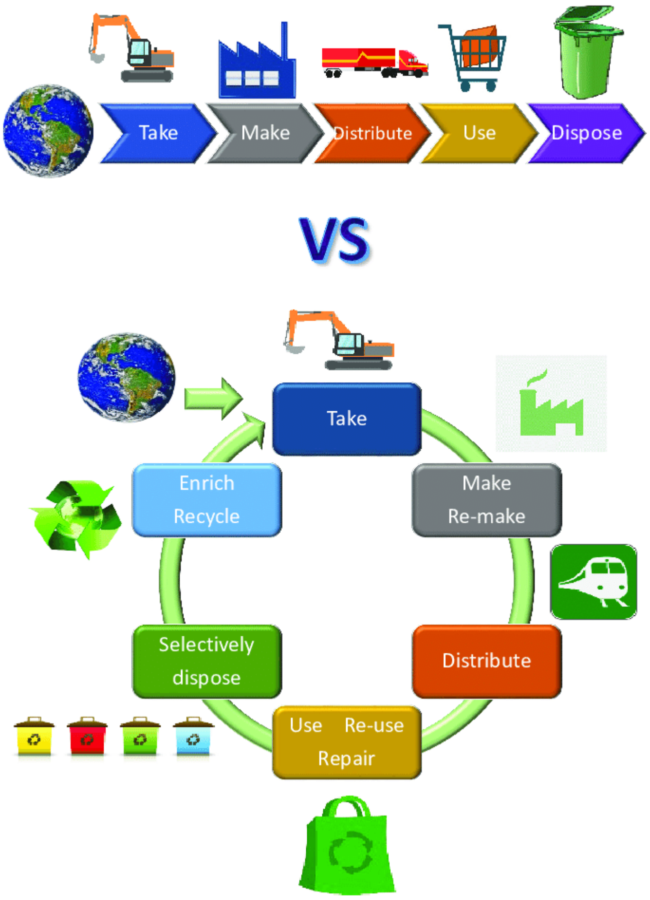

Fig. 1: Illustrating a comparison between linear and circular economy [17].

Although a circular economy provides many advantages, the majority of buildings still exist in a linear and non-sustainable state. This is primarily caused by increased initial costs, insufficient knowledge on the long-term costs and benefits of the circular economy, low levels of public awareness, skepticism around the social and financial return on investment, and a lack of political support/incentives [12]. Despite a great deal of literature discussing the benefits of green architecture, there is little current literature that combines the specific drivers and barriers of circularity with the practical capability of emerging digital technologies (e.g. BIM and AI) within a single analytical framework.

Research question: What are the primary motivators and obstacles for the implementation of sustainable circular architecture within high-rise residential buildings? As well as how can technological innovations (BIM & AI for example) contribute to the facilitating transition from a linear construction model toward circular construction model?

Manuscript framework: Following this introduction, the objectives of this research are provided in section 2. Qualitative methodology; the methods of selecting case-study and analyzing its content are detailed in section 3. The foundations for sustainable circular architecture are addressed in section 4. The primary objectives of sustainable circular architecture are documented in section 5. Technologies and digital tools supporting the design of sustainable circular architecture are discussed in section 6. Section 7 investigates the barriers and challenges associated with implementing and adopting circular architecture. In section 8, an extensive case study of Bosco Verticale in Milan is provided. Section 9 discusses the conclusions drawn from the research in response to the research question. Finally, section 10 summarizes the key recommendations presented in this research for policy, practice, and potential future research.

2. Objectives of the study

2.1 Main research aim

This study is focused on providing an in-depth analysis of the practical factors influencing the implementation of sustainable circular architecture and it will specifically examine the Bosco Verticale project located in Milan. The study also provides several recommendations to assist architects, policymakers, and other individuals involved in planning and developing sustainable circular construction.

2.2 Specific objectives

The study will focus on the following analytical objectives to achieve the above aim:

1) Analyze the sustainable circular architecture conceptual framework and the principles that underpin it.

2) Evaluate the sustainable circular architecture specific goals for the built environment.

3) Investigate and categorize, the technical, economic, regulatory and social barriers that hinder the widespread adoption of circular practices.

4) Assess the impact of emerging technologies (e.g., BIM and AI-driven tools) on the transition from linear to circular construction.

2.3 Research propositions (analytical assumptions):

Based on the literature reviewed, this research proposes two analytical propositions to be used in a qualitative study.

P_1: The principles of circular economy can be integrated into high-rise residential buildings to gain a number of environmental benefits such as resource efficiency, less waste produced, more biodiversity. However, there are many economic initial costs, legal limitations, lack of necessary technical skills as well as the need for special maintenance that restricts using these concepts

P_2: Modern technologies such as Building Information Modelling (BIM) and artificial intelligence (AI) can help work on the problems mentioned above.

3. Methodology

In this research, qualitative case study methodology has been used to analyse the features of sustainable circular architecture. The methodology is developed in a way to guarantee its transparency, rigor, and replicability and gives consideration to the main principles of qualitative content analysis.

3.1 Literature search strategy

To create a solid theoretical basis and to understand the best current practices, a systematic literature search was conducted in a number of academic databases such as Scopus, Web of Science, and Google Scholar. The search focused on publications in peer-reviewed journals, conferences, and reports for the period from

2018 to 2025. The following keywords were employed: *circular economy architecture, sustainable design of buildings, Bosco Verticale, BIM circularity, and barriers to circular construction.*

Initially, there were a total of 186 results. After passing through the two stages of screening in which titles and abstracts were first filtered out and then followed by full articles reading. This led to a total of 45 publications being considered very relevant pertaining to the objectives of the research, being that they talked about the case studies, technological integration, and policy framework of circular economy.

3.2 Case study selection and justification

The research employs an in-depth single-case study design, selecting the Bosco Verticale (Vertical Forest) in Milan as the subject of investigation. The justification for this selection is threefold:

First, Bosco Verticale is widely recognized as a pioneering and award-winning project (receiving the LEED Gold certification, the CTBUH urban habitat award, and the international high-rise award), making it an exemplary model of bio-integrated sustainable architecture [5, 9].

Second, as a "successful" or "extreme" case, it provides a critical testing ground for identifying not only the drivers of circularity but also the persistent barriers (technical, economic, and regulatory) that even state-of-the-art projects face.

Third, the availability of abundant empirical data, technical documentation and research papers on this particular project supports the feasibility of a thorough and solid qualitative analysis and meets the requirements for information-rich case selection.

3.3 Analytical rigor, reliability, and bias mitigation

The information obtained from literature resources and case study reports was analysed via thematic content analysis to find out important patterns related to circular economy aims such as durability, reuse, water and energy efficiency, and waste reduction. To guarantee the accuracy and dependability of the analysis of the findings, a coding system was developed beforehand on the basis of main ideas specified during the literature review. The coding was done by two researchers acting separately or by the author and editor jointly.

To mitigate potential researcher bias, a triangulation strategy was employed by cross-verifying findings across multiple data sources, including peer-reviewed journal articles, official project sustainability reports (e.g., LEED documentation), and reputable architectural databases. Moreover, qualitative data interpretation had been under continual discussion with peer colleagues in order to ensure neutrality of interpretation and minimize any biases. Such multilayered system allows making the result valid and reliable and representing the real picture of what was done throughout the project instead of the researcher's personal views.

3.4 Nature of generalization and proposition testing in qualitative research

It should be clear that this research does not intend for statistical generalization or positive empirical hypothesis testing. Instead, this research takes an analytic generalization perspective [21] in which findings from the case study of Bosco Vertical are used to illustrate, modify and challenge theoretical propositions (P_1 and P_2) that are developed from the literature. The selected case is an ideal or "critical" case study of circular design and provides useful specific details in the investigation of exigent factors or motivators, drivers, and barriers.

4. Concept of sustainable circular architecture

Circular architecture is all about using the principles of circular economy and sustainability together to design buildings that are environmentally friendly, financially viable and socially responsible. By taking a holistic approach to how buildings operate as dynamic systems consuming resources and generating waste, circular architects can create a model that meets the criteria for both sustainable development and circular economy principles. Sustainable development is focused on minimizing the ecological footprint of buildings, including reducing the operational carbon emissions associated with their operation and using renewable forms of energy to operate them. Conversely, the circular economy approach focuses on retaining resources for as long as possible through design to create zero waste or pollution during their life cycle [7].

One example of achieving this goal includes using prefabricated off-site, locally-sourced and regenerative circular materials in order to maximize efficiency and minimize waste in the construction phase, as discussed in sustainable building practices. A good example of the successful initiation of this process is the Amsterdam Schoonschip project, which utilizes decentralized energy, water and waste systems to both reduce environmental impacts and increase community self-sustainability while blending seamlessly with the dual mission of sustainability and the circular economy.

5. Goals of sustainable circular architecture

Sustainable circular architecture aims to fulfil a set of objectives outlined in the literature. The main goals include the following ones:

- **Designing for durability:** Sustainable architecture requires thinking about how and where to create buildings that will stand for longer than the temporal duration they were originally built for. In this respect, architects have to be aware that the aging of a building is predetermined by the choice of materials made. Nowadays, sustainable architecture promotes the use of durable and high-quality materials that ensure sustainability for the long terms of a building [4]. Moreover, a number of modern technologies enable the implementation of proactive protective measures allowing for the prevention of even minor damage from being transformed into demolition of the building [15].

- **Reuse:** Buildings should be designed with components that can be easily interchanged or disassembled. This ensures that buildings can be reused in the future and are suitable for any future construction work [14]. There is less need to make use of raw materials and production of materials is less energy unnecessarily [8]. The salvaged materials can be put to use in making new buildings thereby extending the period of use.

- **Sustainable materials:** Recycled and renewable locally sourced construction materials reduce the amount of carbon emitted from extracting and transporting materials when construction projects use recycled or locally sourced materials [10]. These types of materials include reclaimed wood or recycled steel, which prevent waste from entering a landfill and also reduce energy use needed for producing new materials. Additionally, by sourcing materials locally, there are additional reductions in carbon emissions from transportation. Furthermore, local sourcing strengthens the local economy and creates sustainable supply chains. For example, local sourcing provides jobs at the quarries, mills, or factories that process these materials and indirectly supports other local businesses, such as transportation or repairing tools and equipment. By promoting the recirculation of funds within a community, local sourcing creates a much stronger, resilient, and economically sustainable supply chain. Emerging materials technology is finding new and better ways to support sustainable design and/or construction practices. Upcycled materials are allowing an increased number of waste materials to be used and at the same time provide ways for architects to practice sustainable design [4].

- **Waste reduction:** Through a holistic approach that addresses design, construction, use, and end-of-life stages, architects should investigate new, efficient practices in material specification, precise quantity of materials, and utilization of durable, low-maintenance materials at the design phase. Segregation systems of recyclable materials including steel, wood, and glass should observe on-site waste management during construction to curb continuous landfill establishment. Within a building life, inspection, operation, and modular upgrades will be made. For the end-of-life stage, deconstruction must be part of the plan; mechanical fasteners should be used instead of permanent bonds to allow compartment disassembly and re-use instead of demolition [14].

- **Effective water management:** The foundation of sustainable circular architecture is effectively managing water. Updated methods incorporating the concepts of a circular economy will support waste diversions and better utilize resources; such as rainwater harvesting systems that utilize stormwater for irrigation, toilet flushing, and other applications which will lead to less demand for freshwater. Grey water recycling uses methods that purify water used lightly. (like in a toilet). These systems provide secondary applications for 'grey' water thereby enabling closed systems where the water is reused within the structure. Native plants and landscapes also help conserve water through their efficient use of locally adapted plant materials. The application of these technologies supports water conservation, reduces costs, and assists in meeting the goals set by the circular economy, thereby renewing our limited freshwater resources.

- **Energy efficient design:** The combination of energy efficient design with circular principles represents an essential building block for sustainable circular architecture which aims to provide an environmentally sound means of creating buildings and reducing energy use. The application of passive solar design maximizes the potential of sunlight and heat through establishing a sustainable orientation of the building combined with adequate insulation levels. The incorporation of natural ventilation will enable the introduction of moving air which will provide comfortable cooling without needing mechanical appliances to supply the cooling effect. One example of how an environmental design can use high-performance materials, including insulation made from recycled materials, to reduce heat loss or gain, resulting in the increased thermal efficiency of the building. It is also possible to integrate renewable sources of energy, such as solar panels, into a construction project over time. An example of this is the Schoonschip Project in Amsterdam which has 100 residential units that utilise solar energy to reduce their carbon footprint. This demonstrates the effectiveness of these types of strategies to not only assist in reducing the amount of energy consumed by the building, but to also provide a source of clean energy thereby providing an alternative to fossil fuel energy sources and striving for a more sustainable and environmentally friendly solution to architecture [1].

- **Community engagement:** Incorporating the input of community residents and other stakeholders into the decision-making process of an architecture project helps develop a built environment which meets both the needs of its users as well as the requirements of the ecosystem. To facilitate this process, architects may implement tools that use participatory mapping and/or virtual reality software to foster greater human wellbeing for both the environment and the individual. Therefore, participatory mapping and virtual reality provide examples of how architects can apply a holistic sustainability approach [11].

6. Technological innovations and tools for sustainable circular design

In the realm of architecture, we can define sustainable circular design as a fusion of sustainability and circular economy principles, where the goal is to minimize waste, maximize reuse, and restore natural systems. As previously mentioned, technology will play a role in supporting this transition by offering tools that improve efficiency, optimize resources, and reduce environmental impacts in the construction industry.

6.1 Digital design tools

Digital tools, for example Arup’s circular buildings toolkit, produced with the Ellen MacArthur foundation, lend guidance to architects in moving towards circularity. The circular buildings toolkit promotes low-carbon material usage and design for disassembly, and addresses a key industry challenge, the loss of 95% material value when materials and buildings become obsolete, by helping the architect broaden their view to see a library of case studies and better understand application. Autodesk’s Revit, which provides software design for lifecycle planning, also directly supports the architects' understanding of the reuse of materials, and supports a sustainable outcome the designer can visualize [18].

6.2 AI-driven solutions

AI is changing sustainable circular design in that both the design process and construction elements can be optimized in the scope for circularity by utilizing AI. Autodesk’s forma is an example of an AI construction tool which allows for real-time review and analysis of the designs for a number of components, including embodied carbon and energy use. The Phoenix project in West Oakland is an example of Forma being applied and implemented to allow for a reduction in the design time from two weeks to six hours, while ensuring carbon footprint was mitigated using carbon-negative facades. In addition to the design process, AI directly influences circularity during the construction process, as it is possible to increase the circularity of a building's materials by using robotic deconstruction and waste sorting. ZenRobotics develops robots, such as their ZenBrain tool, which sorts construction waste at 200 tons per hour. The construction robotics market will reach $2.06 billion in value by 2032, which shows how AI is playing an increasingly important role in the construction industry.

6.3 Building Information Modeling (BIM)

Building Information Modeling (BIM) advances the mission for circular design by providing extensive planning elements related to deconstruction and material tracking. BIM tools implement the use of digital planning "material passports", which document the components of a building and track their potential for reuse when the building reaches its end of life. Research has demonstrated that the application of BIM is valuable to assess a project's circularity early on in the design process, and there are existing frameworks that integrate Autodesk's Revit for planning for disassembly [2]. BIM is a valuable tool to support assessing a building's value as a repurposed and reused structure, meaning it is not simply sustainable while actively being used, but allows additional sustainable possibilities once demolition or deconstruction occurs. Furthermore, BIM facilitates collaboration among stakeholders, enabling data sharing on material quantities, specifications, and lifecycle performance, which is essential for implementing circular economy principles in large-scale construction projects [15].

7. Challenges and barriers of sustainable circular architecture

Sustainable circular architecture aims to merge sustainability with the principles of the circular economy to avoid the wastage of valuable resources, reuse materials, and reduce the environmental impacts of the built environment. Nevertheless, many challenges and obstacles to adopting sustainable circular methods exist in the technical, economic, regulatory, and social fields [12, 14].

7.1 Technical challenges

The technical limitation is a significant problem. There are limited options for materials that can actually be formed into a circular design. Sourcing durable or recyclable materials that are also easy to disassemble and reuse is difficult, because many conventional materials are single-use or permanent. Moreover, even if an appropriate material can be selected, there may be difficulties with using a proper skill and construction method to create a disassemblable construction. This is still generally rare and not the norm. Retrofitting older stock for circularity also creates further difficulties, as often their rigid designs make changing the building significantly more difficult and landlords often require the building to be demolished instead of reused. As noted by Kanters [12] and Minunno [14], the lack of standardized design-for-disassembly protocols remains a critical technical hurdle.

7.2 Economic barriers

Economic elements contribute to the issue for the sustainable circular economy because of the high initial costs, with the barrier being priority to overcome. Circular materials, members, and prefabricated walls that can later be disassembled typically have higher upfront costs than other products. However, many times these materials have the potential to provide long term savings by reducing waste and reliance on virgin resources for both individuals and organizations. Both landlords and investors have traditionally operated on much shorter timeframes, so the long-term benefit for their resources is of little interest to them. Market conditions for reuse or recycle products are considered underdeveloped and lack scale and infrastructure to compete on a cost basis with new-product materials; therefore, the focus of many developers has been directed away from utilizing reuse and recycling resources. This short-term financial perspective is a well-documented obstacle in circular economy literature [4, 16].

7.3 Regulatory and policy hurdles

Many instances of regulatory agencies and local building officials slowing down or preventing progress on the transition to circular architecture also exist. Many jurisdictions do not have legislation or regulation in place that clarifies what circular practices are, leaving architects and builders without consistent standards. Where legislation has been established, enforcement may be difficult due to outdated building codes that do not prioritize circular construction practices. In addition, disparities in the enforcement of circular practices across jurisdictions create uncertainty and result in inconsistency for the successful transition into and implementation of circular architecture at the project or specific site level. According to Charef [2], existing building codes rarely incorporate circularity metrics, creating a significant policy gap.

7.4 Social and cultural barriers

Socially, the lack of familiarity and acceptance represents a barrier. Many architects and construction professionals lack sufficient knowledge of circular design processes and will have to be re-trained to utilize them. This training must bridge critical gaps in practical skills such as design for disassembly, the creation and use of digital material passports, and the technical evaluation of recycled building products. For clients and the general public, there may be resistance to using recycled materials as they may be perceived as lesser (in quality or attractiveness), regardless of their environmental merits. While demand is low, due to a lack of awareness in benefits of circular practices, slow-burn momentum is squandered. The perception of recycled materials as inferior quality is a documented social barrier that requires targeted educational interventions [11].

8. Case study: Bosco Verticale (vertical forest), Milan

Bosco Verticale is the pioneering and most representative of the greenery covered high-rise building model. Designed by the Boeri studio team (Stefano Boeri, Gianandrea Barreca, and Giovanni La Varra) and completed in October 2014. This project is celebrated as a revolutionary approach, a template for sustainable residential architecture that has influenced various projects globally. This luxury residential tower complex, located in Milan, Italy, features two structures that reach heights of 80 meters and 112 meters, with a cost of 48 million euro. The building contains 480 large and medium trees along with 300 smaller trees and incorporates 11,000 perennial plants and 5,000 shrubs. The trees with the height up to 9 meters located on balconies of the tower all around, creating peculiar forest across the height of the building. The project offers 30,000 m^2 of woodland on a 3,000 m^2 footprint. The choice and layout of plant species emerged from three years of joint research with botanists and ethologists based on the direction and height of the building façades. The overall green coverage of the towers is about 40% of the total vertical surface area. A few years after it was built, the Vertical Forest has created a habitat that is home to many animal species, including around 1,600 birds and butterflies [5]. This has led to a resurgence of spontaneous plant and animal life in the city. In contrast to traditional “mineral” facades made of glass or stone, the plant-based shield does not merely reflect or amplify sunlight; it filters it, creating a comfortable internal microclimate that is sustainable (Fig. 2). Additionally, this green curtain aids in regulating humidity, produces oxygen, and absorbs CO_2 and microparticles. These remarkable attributes have garnered the project several prestigious awards, including [9]:

- The international high-rise award in 2014
- The LEED Gold certification in 2015
- The best tall building worldwide award in 2015
- The Architizer A+ award in 2016
- The CTBUH urban habitat award in 2016

Fig. 2: The external facades of the Bosco Verticale towers, Milan [5].

9. Results and discussion

This study examines the Vertical Forest (Bosco Verticale) Project according to its adherence to circular architecture principles and sustainability. In addition, the study assesses how the project meets all of the necessary criteria required for circular buildings (e.g., durability/long life, reuse, minimizing waste, energy efficiency, water management, sustainable materials, community engagement). Ultimately, this analysis will identify some of the barriers associated with implementing this type of project. All conclusions have been drawn from empirical literature and technical case study.

9.1 Designing for durability

The research question focusing on the drivers behind circularity is positively answered through the study of the Bosco Verticale showing that the integration of biodiversity is an important factor in ensuring long-term building resilience. Through the diverse number of plant species, they will provide habitat and thereby attract birds and insects, among other wild animals, to create a self-sustaining ecosystem within the densely populated city of Milan. The positive integration of biodiversity as part of the Bosco Verticale's development will enhance the ability of the towers to adapt to fluctuating environmental conditions and will reduce the frequency that requires any form of intervention. Living walls are naturally growing elements that will continue to develop and mature over time, contrasting with traditional buildings that will gradually deteriorate and require periodic renovation. Biophilic design supports the resident's physical and mental wellness by providing a connection with nature while also reinforcing the role of the towers as stable, adaptable residences [6]. However, this driver is offset by considerable obstacles, including relatively high construction costs and special maintenance requirements; these topics will be addressed in section 9.7.

9.2 Reuse

The project is an illustrative example of reuse, which converts vertical urban surfaces to imitate trees in the Forest Canopy, reclaiming space above ground level and providing new habitat for insects and birds. This strategy demonstrates circular examples by creating maximum possible re-use of current built form in the urban environment, and provides for more biodiversity [13].

9.3 Efficient energy design

The trees in Bosco Verticale cleanse the air of CO_2 and produce oxygen without energy-intensive mechanical systems, absorbing approximately 30 tons of CO_2 annually and generating 20 tons of O_2 [16]. This natural filtration reduces reliance on artificial systems. Besides providing shade, vegetation also helps insulate buildings, resulting in less demand for heating/cooling (Fig. 3) [13]. This illustrates the potential for using circular design strategies to facilitate energy efficiency through the inclusion of biological functions within the built environment in overall energy consumption.

Fig. 3: The vertical forest helps to protect the external façade of the towers from the external heat [5].

9.4 Effective water management

Bosco Verticale features a fully automated irrigation system which utilizes greywater coming from the households living in it. This ensures that all types of plants, whether they are smaller or up to 9 meters tall trees, always have access to irrigation. Additional to that, rainwater is also collected to make sure that the dependence on municipal supplies of freshwater is reduced to a minimum [5] (Fig. 4).

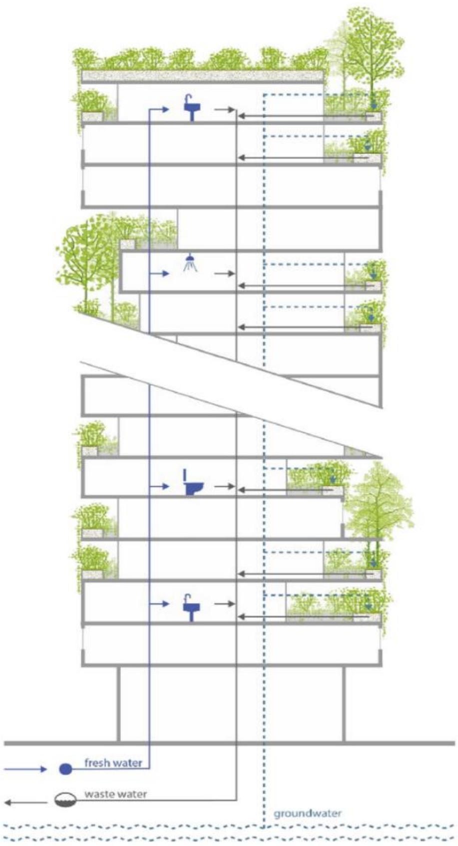

Fig. 4: Bosco Verticale: groundwater is used for irrigation and loads the sewerage system additionally [20].

9.5 Sustainable materials
The towers are constructed using reinforced concrete along with steel planters built for both endurance and the ability to be structurally supportive and so as to minimize early failure [1]. The use of double- and triple-glazed windows provides thermal insulation thus fulfilling the objectives of saving energy [4]. Although the upfront costs are significant, the usage of these materials lengthens the lifetime of the structure by complying with circular economy principles.

9.6 Community engagement
Community engagement has always been considered as an important factor in the project. During the early design stages of the project (2010–2012), participatory workshops and public consultations were held with community members and residents as well as with business representatives, authorities, and municipal stakeholders. The workshops reviewed such issues and concerns as visual impact, personal privacy and insects' gathering in the area, and as a result, some decisions were made about the plant selection and placement of trees, so that there would be no shading and nuisance. In addition, it was decided to set up the permanent committee of residents to manage the maintenance of the forest including such aspects as noise problems connected with irrigation and leaf dropping. This participatory method not only created a sense of ownership in the community, but also taught valuable lessons for other future vertical forests with regard to clear communication as well as adaptability [5, 13].

9.7 Barriers and limitations
In spite of being successful, Bosco Verticale is still confronted with a lot of challenges. Custom-made reinforced concrete and metal frames increase the construction cost, which makes the project expensive for municipalities with limited budgets [12]. In other words, dwelling units in the project may become off-limits to low-income individuals, and this in turn exacerbates the social problems that sustainable development seeks to solve or at least mitigate their negative effects on communities. Maintenance that involves tending to the plants including watering, pruning, and replacing requires specialized equipment and skilled personnel, which makes it costly to run. While the irrigation systems in Bosco Verticale are automated and efficient, their installation can be a costly affair. The construction must also be done in a strict engineering manner, which guarantees that the building can withstand all external forces like wind and earthquake. In addition, the plants may also attract mosquitoes and insects and hence more than the normal rates of utility bills are expected to be paid.

9.7.1 Methodological limitations of the study

As well as offering these practical insights, some methodological determinants must also be highlighted concerning this study.

First, the single-case study design chosen means that the findings cannot necessarily be generalized; although still informative, the case of Bosco Verticale may therefore be an unrepresentative example.

Second, because this study relies entirely on secondary data, it does not capture the firsthand perspectives of residents, facility managers, or policymakers.

Third, although triangulation and verification of inter-coding procedures were conducted, qualitative content analysis means that the research must be interpreted by the researcher.

Finally, the Milan context also works against straightforward application of these findings to other contexts, climates and regulatory regimes as additional comparative and longitudinal research needs to be conducted to verify and increase the accuracy of the findings.

10. Conclusion

The study set out to perform an in-depth investigation of the challenges and possibilities present in the context of sustainable circular architecture by way of case study of “Bosco Verticale” in Milan, Italy. Utilizing qualitative content analysis, the research focuses on the design, installation, and environmental performance of the involved construction to provide some important revelations.

Bosco Verticale seems to have showcased how to integrate ideas of circular economy into high-rise residential architecture. The project has demonstrated circularity by means of biodiversity – absorbing the 30 tons of CO_2 emissions and hosting more than 1,600 types of species; greywater reuse, using sustainable resources and energy conserving systems.

However, the study also identifies persistent barriers that hinder the widespread adoption of circular architecture. Such impediments are high initial investments, unique maintenance requirements, complex structural demands, and lack of governmental regulations or incentives. Even a landmark project like Bosco Verticale has encountered problems similar to those faced by other projects, bringing about a need for change in the approach to the project in order to come up with appropriate legislation, financing options or the way architects are educated.

The research points out that in the context of the above issues, technology, especially in the form of BIM and AI, plays a significant role in solving the issues. BIM allows for the tracking of materials and life cycle assessment thanks to digital "material passports", while AI makes it possible to predict maintenance schedules or sort waste materials. While these technologies are still new and need much improvement, they have great potential for further developing circular design.

10.1 Recommendations for practice and policy

Based on the findings, the study recommends that:

- **Policymakers** develop clearer regulatory frameworks and incentives to support circular design and construction.
- **Architects and engineers** adopt design-for-disassembly principles and invest in training for circular skills.
- **Financial institutions** explore long-term investment models that account for lifecycle savings rather than initial costs.

10.2 Limitations and future research

The study acknowledges its methodological limitations, including its reliance on a single-case design and secondary data. While the findings are analytically generalizable, they are not statistically representative.

10.3 Future research directions include:

1. **Comparative case studies** across different geographical and climatic contexts to validate the transferability of circular principles.
2. **Empirical research** employing primary data collection (interviews, surveys) to capture stakeholder perspectives and behavioral dimensions.
3. **Longitudinal studies** tracking the long-term performance, lifecycle costs, and user satisfaction of existing circular buildings.

10.4 Final remarks

In conclusion, sustainable circular architecture is a paradigm shift from static, resource-intensive buildings to dynamic, regenerative systems. Case study of "Bosco Verticale" shows that this transition is not only possible but also impactful. However, the large-scale implementation of this concept calls for collaboration among engineering, policy, finance, and education actors. By overcoming the barriers, we have identified and using the available technologies, we can advance the implementation of circular economy principles in the built environment.

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