

Review

Waste Management and Operational Energy for Sustainable Buildings: A Review

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Abstract: Construction and demolition waste account for a significant part of the solid waste taking up landfills on a global scale. A considerable portion of the waste generated by the construction industry has substantial residual value, and therefore waste management and sustainability principles and techniques should be applied. Buildings consume a lot of energy during the operations phase, but decisions made during design and construction impact building operations. This study reviews sustainable building practices to explore strategies that ensure minimal effects on economy, society, and the environment through efficient resource and waste management at different phases of a building life cycle. These practices include pollution reduction, reuse and recycling, energy consumption, embodied carbon, and water resource management.

Keywords: waste management; reuse and recycling; embodied carbon; indoor air quality; smart building operation; energy efficiency

1. Introduction

The United States Environmental Protection Agency (US EPA) claims that the United States generated 136 million tons of construction waste in 1996 [1,2] and 569 million tons in 2017, more than twice the amount of municipal solid waste [2]. The escalation of construction waste dumped in landfills is staggering, especially considering that most construction waste can be recycled. Globally, construction and demolition (C&D) is the most significant contributor of waste [3], continually increasing landfill waste and producing more methane, a principal factor in climate change [1]. The United Kingdom alone can generate over 120 million tonnes of construction, demolition, and excavation waste each year [4] while in the European Union, over 450 million tonnes of C&D waste is produced yearly [5]. Redirecting C&D waste would likely produce measurable results since this amounts to a large percentage of overall waste. Industry professionals can practice reduce, reuse, and recycle techniques during design, construction, and occupancy to minimize waste generation and disposal.

Building occupancy and operations cause further detrimental impacts on the environment. Residential and commercial buildings account for nearly 40% of global energy consumption [6]. According to the US Energy Information Administration (US EIA), in 2019, primary energy consumption in the US was about 2527 Mtoe (100.2 Quadrillion Btu), and primary energy consumption per capita was 7.69 toe (305 Million Btu) [7]. Globally, humans used about 14,501 Mtoe (575 Quadrillion Btu) of energy in 2015 [8]. In 2019, 62.7% of utility-scale electricity was produced from fossil fuels such as natural gas (38.4%), coal (23.5%), and petroleum (0.5%) [9]. Escalating growth in energy demand led

to a 2% increase in carbon emissions associated with energy use in 2018 [10]. Renewables like wind, solar, and geothermal accounted for 24% of global electricity generation in 2016 and rose to 26.2% in 2018 [11,12].

Sustainable design and construction mainly focus on minimizing adverse environmental, social and economic impacts of buildings. Rapid development in many countries across the globe has resulted in generating significant unmanageable construction waste, thus creating considerable negative impacts on the environment such as increased soil, water, and air pollution, which contribute to climate change, health hazards, and ecological imbalance. In addition, poor design and construction practices have significant life cycle economic and environmental impacts, resulting in the waste of energy and material resources [13].

This study reviews sustainable building construction and operations to explore strategies that ensure minimal effects on costs, society, and the environment through efficient resource management at different phases of a building life cycle. The remaining sections of this article are outlined as follows. Section 2 presents the research methodology. Section 3 includes the findings from the review of the literature focused on waste management strategies and energy-saving technologies for buildings that have already proven their effectiveness in practice. Section 4 presents conclusions and future research directions.

2. Research Methodology

The authors identified, analyzed, and reported their literature review by using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) tool, specifically adopting guidelines in the PRISMA flow diagram and PRISMA checklist [14]. PRISMA uses systematic and statistical practices to pinpoint and analytically review related research and to gather and examine the information from the studies that were included in the review. The PRISMA flow diagram offers four phased criteria to guide the authors in their research: identification, screening, eligibility, and inclusion (Figure 1) [15].

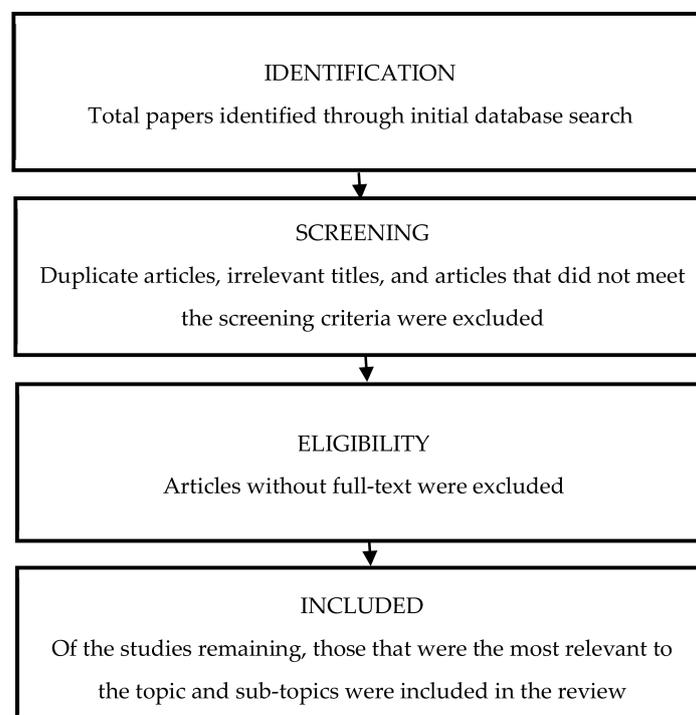


Figure 1. Simplified flow chart showing the selection process for the articles.

During the identification phase, the authors identified potential papers through database services including ASCE Civil Engineering Database, Compendex, Proquest, SAGE journals, SpringerLink, Scopus, Web of Science, IOPScience, and Google Scholar by using selected keywords in the search strategy. Keywords related to a selection of subtopics in Table 1 were used in the search. Some of the keywords used include pollution reduction, design, construction waste, waste management, reuse and recycling of building materials, embodied carbon, sustainable construction, water waste, water harvesting, natural bio solutions, Indoor Air Quality (IAQ), Indoor Environmental Quality (IEQ), smart building, technology, smart home, building energy consumption reduction, building energy efficiency, and building energy-saving strategies. Subsequently, the papers found were screened for relevance and eligibility using a selection of defined criteria including checking the number of citations and the journal impact factor. The authors used the PRISMA checklist to assess the quality of the identified sources; only the most relevant papers were included in the article. A variety of filters was also applied to the search to narrow the results, such as specifying a period to eliminate articles that fell outside the specified timeframe. Both journal and non-journal articles were included.

Table 1. Top three keywords searched for each subtopic.

No	Sub-Topic	Top Three Keywords
1	Designing for limited construction waste	Design, construction waste, prefabrication
2	Pollution reduction	Pollution reduction, green building, waste management
3	Reuse and recycling	Recycling, reuse, life cycle assessment
4	Embodied carbon	Embodied carbon, embodied energy, sustainable construction
5	Water-saving construction process	Waste water, water harvesting, bio natural solutions
6	Energy consumption	Building energy consumption, building energy efficiency, building energy-saving strategies
7	Indoor Air Quality (IAQ)	IAQ, Indoor Environmental Quality (IEQ), air pollutants
8	Smart building monitors	Smart building, smart grid, smart meter

Out of 667,153 results from initial searches, before any filters were applied, 667,070 sources were excluded due to criteria such as duplication, title irrelevance, and inappropriate full text and methods. Other sources were included from supplementary searches. Ultimately, only 111 sources were included in the manuscript.

3. Findings

3.1. Waste Management in Buildings

3.1.1. Designing for Limited Construction Waste

Designer's Role

Architectural and engineering decisions can have a significant impact on the amount of waste generated during the construction phase. The design phase of construction is the best opportunity to address waste management. Architects and engineers—the designers—are the first line of defense against a project riddled with waste generation: their decisive role for managing waste effectively is by focusing on designing it out of the project [16,17]. The most substantial amount of on-site construction waste is the result of inefficient design decisions [3], and about one-third of all on-site waste is generated by architects' failure to implement waste reduction measures in the design phase [16]. Aesthetics and client requests could play a role in a limited number of design management measures; therefore, it is the responsibility of architects to enact measures on their own. Designers can include waste management solutions in their designs, showing and educating clients on the economic, social, and environmental

benefits [3]. Designing out waste can be a challenging task, so the Waste and Resource Action Program (WRAP) divides the idea into five principles: (1) design for reuse and recovery, (2) design for off-site construction, (3) design for materials' optimization, (4) design for waste efficient procurement, and (5) design for deconstruction and flexibility [4].

Engaging an Integrated Project Delivery (IPD) method will aid in implementing effective waste management techniques. As clients, owners, architects, engineers, and contractors are all integrated into the project from the design phase to the construction of the building, the team can develop and agree to suitable waste management practices. "A hallmark of integrated waste management includes preventing waste from being generated in the first place" [1]. Therefore, it is of the highest priority that architects keep the construction process in mind [18] as it is a collective effort from the individuals and trades that is responsible for the entire construction process.

Offsite Fabrication/Standardization

Building components designed to be manufactured off-site streamline on-site construction. The benefits of off-site prefabrication and precasting include reduced construction-related transportation, accident avoidance, improved workmanship quality by reducing errors, rework, and damages, reduced waste, and improved construction schedules [4,16]. Prefabricated buildings have a lower environmental impact during the construction and end-of-life phases because of lower emissions and water and energy consumption [19]. For example, prefabrication is one of the top two most recommended solutions for minimizing concrete waste (procurement management is the other) [20]. It can be argued that the transportation of prefabricated components is actually less sustainable than on-site fabrication, but there are many factors to consider with transportation. Effective management of completely finished components could prove to be more sustainable than transporting all sub-components and fabricating on site [21]. Some designers argue that there is limited aesthetic value to pre-manufactured building components [22], even though prefabricated housing has become more mainstream [1]. However, aesthetics is a matter of opinion; prefabrication is a matter of sustainability, similar to standardization.

Standardization is a waste-reducing practice that limits the quantity of material cutoffs [16,17]. A major cause of the great number of on-site offcuts is due to the lack of standardization and dimensional coordination [17]. On-site construction incorporates field measurements that could be prone to errors and material overages in procurement and dimensionality. Irregular shapes and dimensioning that are not compatible with standard material sizes cause cutting waste; thus, architects and engineers can design and layout systems using dimensions coordinating with material sizes so that less measuring and offcuts are needed in the construction phase [22,23]. Conforming to the standard building material sizes of drywall, brick, concrete masonry unit (CMU), piping, and conduit can reduce on-site waste, limiting the need for site debris-sorting and hauling fees [16]. Standard designs can be fabricated in a controlled environment; then, buildability on-site improves due to limited trades on-site and field cutting, allowing for a rapid assembly of parts [4,16]. Industry professionals have seen an increased number of prefabricated buildings and modular systems [18]. Designers can identify which pieces of the building design can be manufactured or fabricated off-site and use the designed Building Information Modeling (BIM) model for the production or cutting of components. As described below, BIM is the most important tool that designers can use to limit construction waste.

BIM for Waste Reduction

Construction drawings and specifications are the most important documents used on a project. Poor design decisions can lead to massive amounts of waste being generated. Up to one-third of construction waste is commonly generated from improper design and changes [20,24]. BIM stores large-scale data [17] that allow all parties to visualize the project, detecting problem areas to be remedied and creating extractable information that can be used to construct the building efficiently. The ability to identify clashes, improper design techniques, schedules and costs during the design phases facilitates collaboration [18], thus improving waste management, as all involved parties are involved from start

to finish [3]. BIM has been shown to reduce on-site construction waste by 15–32% [3,24]. By digitally identifying clashes and poor design early—before construction—those problems are avoided on-site [3] by reducing change orders, time for rework and costs, and limiting any potentially generated waste [16]. As the model can be accessed by the entire project team, contractors can generate material takeoffs easily and export material lists (sometimes with costs and model number) for easy ordering [20,24].

BIM can reduce drawing inefficiencies and, therefore, waste generated. Won [20] performed two case studies for waste management in South Korea. The first case involved two residential units with a total floor area of about 120,000 m² and the second case involved a sports complex comprising a baseball facility and a clubhouse with a total floor area of 9995 m². The first case identified that almost 48% of design errors were the result of discrepancies between drawings; the second case identified that 57% of design errors were the result of illogical design [20]. Drawing discrepancies and illogical designs accounted for 69% and 71% of total rework on case 1 and case 2, respectively [20]. Won estimated that the construction waste reduction rates would be 15.2% for case 1 and 4.3% for case 2 if BIM was incorporated [20].

Gavilan [25] performed case studies on four different projects in which the contracting firm size differed—two small companies, one mid-size, and one large company in the US—and found equal results: the size of the company did not affect waste management [25]. The study concluded that waste was “closely linked to the traditional sources of low productivity” and organized the sources into six categories, including overall design, design changes, and drawing and detail errors [25]. Waste is generated from these design mistakes because of rework: if the contractor has constructed the component(s) and is required to remove and reconstruct, materials are not likely able to be salvaged [25]. BIM could have solved the mentioned three of six waste problems identified. The design would have been modeled correctly, with clash detection performed by all trades, thus avoiding poor design and poor drawing documents, limiting the design changes needed.

BIM's uses continue past the design phase, providing efficiencies through construction, commissioning, and operations. One of the most significant uses of the BIM model is the extraction of data for use in subsequent phases of construction, integrating multiple technologies and programs into the design process [3,17]. Waste can be managed efficiently by extracting all relevant information, elements and specifications from BIM software. Instead of reading shop drawings, measuring, and laying out, the BIM geometry can be exported for use in fabrication programs [16]. The fabrication is automated and produces components exactly as modeled in the drawings. The importance of off-site fabrication was discussed in the previous section. Once constructed, the final model can be submitted to the owner to use for operations and maintenance purposes throughout the life of the building. As the model is an exact digital replica, renovations and maintenance tasks could, again, use BIM for clash detection, scheduling, and material takeoffs.

BIM is a collaborative effort of all stakeholders involved in a project. Using the model to experience the project as a complete entity enables cohesive and complete understanding from designers, contractors, and owners and, as a result, produces a fully unified design, construction, and operation package that effectively limits the amount of waste generated.

3.1.2. Waste Management and Pollution Reduction

Pollution reduction is one of the most effective ways of achieving sustainable buildings and managing waste particularly because buildings are responsible for releasing a wide range of pollutants, including toxic dust and other air pollutants, harmful solid wastes, water pollutants, and noise pollution. Generally, the triple bottom line (TBL) is an important accounting framework in sustainability, which takes into account three important dimensions, namely the social, financial and environmental performance of building and construction projects [26]. The social sustainability aspect of TBL requires that green buildings must take into account the potential social impacts of the building and construction project on the local community. This can be achieved by employing the locals during the construction

process and designing buildings that promote the health of its occupants, but social sustainability involves numerous other aspects and needs to be more robust [27].

The financial aspect of sustainable building involves the economic viability of construction projects that have the potential to create economic benefits for investors, the local community, and society as a whole. One way to measure this is by estimating the life cycle economic and environmental impacts of the materials selected for the building.

Environmental sustainability in construction projects largely involves employing sustainable building practices that increase pollution reduction and have a minimum impact on the environment [28]. Sustainable buildings use a variety of pollution reduction strategies. For example, the problem of air pollution in building and construction is addressed by dampening construction dust through fine water sprays, limiting the burning of toxic wastes in construction sites, and using locally sourced sustainable construction materials [25]. Water pollution reduction is achieved by effectively monitoring the disposal of waste through recycling. Finally, noise pollution is reduced by installing acoustic barriers, using properly maintained equipment, and wearing appropriate gear to protect hearing loss among construction workers. Other strategies for pollution reduction include material selection and implementing proper waste management.

Building Design and Material Selection

Optimized building design, siting, and proper material selection are important components of the TBL and contribute to waste reduction. In sustainable building, the selected sites should minimize urban sprawl and avoid the potential destruction of natural habitats, designing buildings in a way that not only reduces their impact on the environment but also minimizes energy use while using appropriate materials that enhance the durability of the building and improve its performance [29]. This can be achieved by utilizing existing natural hydrological features such as the flow of stormwater during site selection in order to minimize the building footprint on the site of the construction [30]. In addition, it is important to select appropriate materials that provide thermal insulation, enhance energy efficiency, and reduce pollution and energy waste. For example, high-performance low-e glazing is critically important in achieving optimum energy performance in buildings. Similarly, the use of energy-efficient light bulbs that incorporate sensors may also reduce energy use in buildings.

Reuse and Recycling of Building Materials

Reuse and recycling is an essential strategy that helps to reduce the environmental impact of buildings. A good principle to follow is reduce first, reuse, and then recycle. Reusing and recycling are distinct terms that are not interchangeable, even though they attempt to achieve a common goal. Recycling keeps materials out of the landfill by “collecting, segregating, processing, and manufacturing collected goods into new products” [31]. Through the process of reusing, materials are kept out of the waste stream and landfills by passing collected goods on to others [31]. This, in turn, increases the wellbeing of our communities by allowing citizens to make useful products that have been discarded by others who are no longer in need of those products. From an environmental perspective, reuse programs reduce air, water, and land pollution and limit the use of natural resources [31]. From an economic perspective, reusing can help people from all socioeconomic backgrounds to obtain the items they need in a less expensive way [31].

Incorporating reusable building materials can reduce waste pollution and energy use [31]. Building materials that are environmentally friendly include wood, metals such as steel, aluminum, iron and copper, bricks, concrete, drywall and linoleum flooring, all of which are either biodegradable, reusable, or recyclable. Reusable building materials can be either composed of one substance or can be disassembled into individual materials that can be reused or recycled [31,32]. Construction and demolition account for 30–50% of the US solid waste stream and approximately 85% of the material derived from these activities includes reusable or recyclable material [31]. Therefore, it is important to select materials that can be reused or recycled at the end of their useful life. It is also helpful to select

materials that are longer lasting or have longer life expectancies in order to use the environmental impact of having to replace such materials over a long period [31].

Building construction is one of the most wasteful activities, even though almost every component or material in construction can be reused and renewed [31]. The negative consequences associated with building construction can be avoided by utilizing the concepts of reuse and recycling. The authors of [33] presented some environmentally friendly methods of reducing waste disposal that are categorized by material type. The breakdown per category shows the recycling possibilities in the life cycle of each material, which results in less waste disposal and lower costs. Educating and training people about proper waste management can curb behaviors that are harmful to the environment [33].

Life Cycle Assessment (LCA) evaluates the environmental impact of building materials through different phases of a building [31]. The phases of the product life cycle include raw material, production, transportation, use, and disposal. If certain phases are reduced, or the cycle can skip over a few phases, this will greatly reduce the impact on the environment, cost, and availability of a material [31]. There are different software options, such as Building for Environmental and Economic Sustainability (BEES) and Building Industry Reporting and Design for Sustainability (BIRDS) by the National Institute of Standards and Technology, that can evaluate the environmental, social and economic impact of buildings over a period of time [34]. Implementing these tools can potentially decrease environmental impact, as clients and the design team would be more conscious when choosing materials for their projects [1].

Studies have shown that recycling building materials can reduce environmental impact and total life cycle energy by 30% [35]. During the process of construction and demolition, it is important to consider quality over quantity. In other words, it is important to value the materials to be recycled in terms of effectiveness and sustainability. Within the field of recycling, there are two concepts, known as upcycling and downcycling [36]. Upcycling is the “enhancement of value or utility through non-destructive recycling” [36]. Although some processing is undertaken in upcycling, the impact of the processing should be “less than the impacts of extracting and processing the virgin material displaced by the upcycled product” [36]. Downcycling is the process by which waste materials are converted into something of lesser value. This is normally used on products whose nature prevents them from retaining their former durability once re-processed [36].

Despite the known positives of practicing sustainability, there are legal, technological, and economic barriers that prevent sustainable practices and methods from being implemented to their fullest potential [37]. Unavailability of sustainable materials, direct and indirect costs, lack of ability to enforce sustainability policies and lack of experience are some of the most common issues that hinder the implementation of sustainability on a global scale [37]. Reusing and recycling are practical and economic approaches that embrace and encourage sustainability principles in a way that is accessible to all communities and economies.

Pollution Reduction through Proper Waste Management

Eliminating and reducing waste and increasing the reuse of materials in building and construction projects is another important way of reducing pollution. This involves implementing a number of strategies, such as selecting building products that consider transportation, packaging, and the use of reusable and recyclable materials [38]. Materials eliminated in construction as waste can effectively be reused, thereby reducing pollution and eliminating the financial costs of waste disposal. In addition, effective waste management can also be accomplished by using more durable construction materials and minimizing demolition as a way of reducing pollution and waste creation, since demolition contributes 90% to C&D material waste [39]. Instead of demolition, deconstruction can be adopted in building and construction projects: deconstruction allows for better recovery of reusable materials, thereby minimizing pollution in the form of landfill waste and reducing the cost of construction. The authors of [40] explored sustainable materials management using performance metrics to monitor

solid waste management. There is a need to focus on specific materials in the waste stream to improve the effectiveness of proposed approaches.

3.2. Water-Saving Construction Process

According to United Nations Educational, Scientific and Cultural Organization (UNESCO) and the World Health Organization (WHO), 33%—roughly 3.5 billion people—of the world's population are not granted fresh drinking water [41,42]. Due to global population growth, industrial and agriculture overuse, new lifestyle standards, climate change, and a lack of policies for pollution control, among others, demand trends have steadily increased by 1% on a yearly basis [41,42]. Buildings also account for roughly 12% of the freshwater withdrawals just in the US [43]. Therefore, in efforts to mitigate worldwide water scarcity, water resource management is necessary. This section summarizes how green buildings, by readily available means, play a fundamental role in water conservation, wastewater (WW) management, and, likewise, promote sustainable management practices and waste reduction.

3.2.1. Water Resource Management

There are several conservation techniques and methodologies applied at different stages of the design, construction, and operation of buildings. Although there are many subcategories, there is a distinction between indoor and outdoor water use, so it is vital to clarify their impacts on the environment [44]. Indoor water conservation techniques include smart metering, water use reduction calculators, water-saving fixtures, and greywater recycling that can be applied during the design to obtain various results [45]. The outdoor criteria include the use of alternative resources, such as rainwater harvesting [46], water-efficient landscaping, building natural sources, green technologies and, lately, novel bio-remediation techniques.

Water Metering and Monitoring

Metering systems are strategically installed to monitor water consumption; the data collected can then be evaluated to see if consumption rates were met according to Water Stress Index (WSI). Moreover, by using smart artificial intelligence-based metering systems, it is also possible to monitor occupants' water consumption behavior to eventually incentivize water checks programs [47].

The typical analysis gathers historical water consumption data from sources like (1) Sanitary fixtures (i.e., urinals, lavatories, faucets, sinks, and showers), (2) climate systems that emit condensation during the process, (3) landscape operation (i.e., irrigation, garden watering and/or vertical greeneries), (4) miscellaneous (bathtubs, pools, dishwashers, etc.). Regular models require an analysis of water supply and sewer discharge together with service life, water utility rates, and any technological efficiency system, low flush toilets, low-flow showerheads, or automatic water shut-off valve. The Leadership in Energy and Environmental Design (LEED) standards include a calculator for indoor water use reduction for each fixture type [48].

A Net Present Value (NPV) analysis can be obtained to determine the feasibility of a system [49]. The Internal Rate of Return (IRR) measures profits for potential investments and the Benefit–Cost Ratio (BCR) shows the ratio of the NPV of cash inflow to the NPV of cash outflows [50]. Results can be verified for the Consumptive Water Rates (CWR), Degradative Water Use (DWU), WSI [51], while also ensuring that mandatory regional standards like British Standards Institution (BSI) in the UK, or NSF/ANSI Standard 350 in the USA are met.

Water Recycling

Greywater can be differentiated by the type of treatment required for removal of suspended and slow media, typical home showers, hand and clothes basins or light greywater (LGW), and household toilets and sometimes the kitchen basin, also known as dark greywater (DGW) [52]. Greywater (GW) makes up as much 60% of the domestic wastewater volume [53]. Because of the high potential of domestic water treatment, GW reuse has become an essential practice for preserving freshwater use in

buildings; furthermore, recycling water was clearly identified for the protection of the water sources, recovery of farmland nutrients, groundwater recharge, and to reduce wastewater discharge [54]. Rain water harvesting (RWH) systems provide non-potable water for domestic use and can reduce storm water runoff and potable water demand by 60–80% [55,56].

Nature-Based Alternatives

Nature-based alternatives have been increasingly used in WW treatment to remove larger amounts of organic matter. The authors of [57] presented several nature-based solutions (NBS) for and its application for improving water availability, quality, and risk. These systems offer benefits that extend beyond environmental, such as improving the landscape but also social and economic benefits [57]. Other applications like membrane bioreactors (MBRs), green or vegetated walls, vertical subsurface flow constructed wetlands, constructed artificial wetlands, and green roofs showed high performance while reducing runoff [58]. Typically, these systems can be designed to harvest rainwater into a reservoir with sufficient capacity to retain and collect it for reuse, an equivalent of up to 60–70% of the total water volume required on gardening and DW. The volume of water depends on regional climate and soil conditions.

Mycelium–biomass composites are emerging as a novel sustainable material with very useful capabilities such as degradable toxics medium [59], such as heavy metals, tobacco smoke, ink, arsenic, coal-tar distilled compounds [60], among others; it is also known that novel mycofilters are able to remove the formation of microbial bodies (e.g., *E. coli*) and pathogens [61]. Overall, mycoremediation represents an approach to treat contaminated soil and water; indeed, combined with a variety of water management applications, it offers itself as a solid eco-tool to clean polluted waters from high-industrialized and congested urban regions.

3.2.2. Build for Resilience

Extreme meteorological changes like storms and hurricanes are resulting in more intensified precipitation and rapid flooding events. Further, extreme climate conditions impede crop growth, risking its continuity. These changes are becoming more frequent; thus, the ramping-up capacities of local communities and cities to manage climate change disruptions is a key factor for future generations to thrive [62]. Green roofs and constructed wetlands reduce stormwater runoff, mitigate heat island in urban areas, allow for food self-production, and serve as an alternative source of water [63,64]. [65] discussed the water-energy nexus and energy production from water and energy for water treatment, desalination, and other purposes. Beneficial synergies in the water-energy nexus should be harnessed to increase the resilience of these systems. LEED from the United States Green Building Council (USGBC) makes available sections focused on integrating these concepts into the building [66,67]. These eco-techniques require complex engineered systems and, in order to serve the core of ‘sustainability,’ these systems should lower Life Cycle Impact (LCI). The standard for water footprint based on LCA (ISO 14046) can be implemented as a tool to ensure that biotechnologies truly fulfil the expected requirements.

3.3. Embodied Carbon and Operational Energy Use

3.3.1. Embodied Carbon

Embodied carbon is the carbon dioxide (CO₂) or greenhouse gas emissions involved with the manufacturing and use of a product or service. The embodied energy of a product correlates to the energy used to build the product: it involves the extraction, refining, processing, transporting, fabricating and demolition involved in the construction. The amount of emissions released in construction and the built environment has been the main cause of carbon increase in the world. To combat this, the world today is moving towards a reduction in embodied carbon. Within the building sector, the urgency to reduce carbon impacts fully and move to net-zero carbon emissions by

2050 was the goal for the Paris Agreement of 2015 [68]. The main objective is to fight climate change, mitigate greenhouse gas emissions, and limit the increase in the world's temperature [68].

Embodied Carbon in Buildings

Globally, communities have committed to reducing carbon emissions by enacting various sustainable measures. Looking at the life cycle stages of a building, it is clear that buildings' lifespan ranges from 50 to 100 years; therefore, buildings must be resilient enough to withstand future impacts [69]. Sustainability in construction separates the life cycle into four different stages: the production stage, the construction stage, the use stage, and the end of life stage. The production stage is typically investigated when determining the emissions released into the environment. During the production stage, raw materials are gathered, extraction takes place, goods are transported, and manufacturing occurs. At the construction stage, the structure is developed, finishes are applied, and the building is prepared for occupancy. The use stage includes the operation and maintenance of the building. Finally, the end of life stage deals with the decommissioning and disposal of materials [70,71]. The life cycle of a building has embodied carbon with associated emissions.

The urban environment has the greatest need for energy savings and emissions reduction, it accounts for 71–76% of global carbon emission and up to 76% global energy consumption [72]. Worldwide building operations account for 28% of energy emissions in relation to greenhouse gases (GHG) [73]. The major components that contribute to an increase in GHG emissions in buildings are space cooling, appliances, and other plug loads [73]. Energy efficient operations of these systems lead to the greatest emission reduction [74].

Reducing Embodied Carbon in Buildings

There have been numerous actions taken globally to reduce the number of emissions and move towards a sustainable future. The UK's carbon calculator, called the Carbon Infrastructure Transformation Tool, revealed that burden-shifting occurs when one stage of the LCA is adjusted, but the overall energy consumption is increased [71]. For example, a high-speed rail project was designed with a smaller train tunnel diameter, therefore reducing the amount of excavation and materials needed. However, by reducing the tunnel diameter, the air resistance within the tunnel was altered, which consequently increased the amount of total energy use [71].

In South Korea, there have been tests to develop voided slabs that are filled with void formers in the middle to reduce the amount of GHG emissions from the materials. Compared to regular concrete slabs, not only did the voided slabs accomplish the same tasks, they did so at a 12% reduction in GHG emissions and lowered overall costs [75].

In the United Kingdom, CEMEX was the first company in 2010 to reveal calculated carbon footprints—cement, concrete, and aggregate products—to their clients [76]. In response, California developed rules and regulations to ensure a move in a sustainable direction. In October 2017, the governor of California approved the Buy Clean California Act (BCCA) that will reduce the amount of carbon emissions and global warming potential (GWP) [76]. Investigating alternative insulating materials is another technique to offset carbon emissions. Rapeseed, an oily plant seed, is used in Europe as an insulation substitute, which provides a 12% reduction in carbon emissions while maintaining the same thermal resistance and comfortability to the inhabitants [77]. The GWP is the extent of global warming impacts of different gases [78]. In a study determining the insulation of various materials, expanded cork was shown to reduce the amount of carbon emissions during the construction phase and lower the GWP overall while providing the optimal thickness needed for heating and cooling [69].

3.3.2. Energy Consumption

The International Energy Agency (IEA) reported an increase of almost double the amount of global energy consumption from 2010 to 2018, which also resulted in a 70% increase in CO₂ emissions [79].

In the US, buildings alone are responsible for approximately 40% of the total energy consumption [80]. Currently, people spend about 90% of their time indoors using more electrical appliances, increasing energy consumption per capita [80,81]. Furthermore, the continuous growth of the average housing size leads to a higher energy demand for space cooling and heating [82]. The growing population spending more time indoors will stimulate a further escalation in both energy consumption and CO₂ emissions associated with building operations.

The primary residential energy consumption categories are space heating (37%), electrical appliances (25%), water heating (19%), followed by space cooling, lighting, and cooking (less than 10% each) [80]. Since coal and natural gas currently constitute 23.5% and 38.4% [9], respectively, of the overall US utility-scale electricity generation, building energy consumption reduction could decrease CO₂ emissions significantly. This section provides an overview of state-of-the-art technologies for building energy consumption reduction and clean, renewable energy generation that can be used for new construction and retrofitting projects to reduce or eliminate the environmental burdens caused by building operation.

Passive Building Energy-Saving Technologies

(1) Building Envelopes

Building envelopes separate the indoor space of a building from the outdoor environment and play an essential role in reduced building energy consumption. A well-insulated building envelope can save up to 22% of energy consumption [83] and reduce GWP, as earlier discussed. As an example, building envelopes that comply with the Passivhaus standard applied in Germany demonstrate 49.7% higher energy efficiency than the envelopes used in Tianjin, China [83].

(2) Window Glazing

Buildings can lose 60% of their energy through windows [84]. The selection of a proper window-to-wall ratio and a window glazing material minimizes heat gain/loss [80]. Near-infrared electrochromic windows may save up to 50% of energy compared to conventional window materials without sacrificing visual comfort [84]. Moreover, windows can generate energy if they are made of semi-transparent building-integrated photovoltaic modules [80].

(3) Passive Heating

Passive heating technologies rely on solar heat energy. One of the typical technologies is the Trombe wall that allows for transferring solar heat energy into buildings to meet a part of a heating load [80]. More advanced building integrated photovoltaic Trombe wall systems generate electrical energy in addition to heat energy [85].

(4) Passive Cooling

Passive cooling can be provided by nighttime ventilation with cold night air, ground cooling, and sun shading technologies [80]. Case studies in Germany, Italy, and Turkey demonstrated 13–44 kWh/m² energy savings due to nighttime ventilation [80]. Ground cooling systems represented by the earth–air heat exchangers can save 38% of electricity consumption compared to electric heaters [86]. A case study of an office building in Athens showed that a green roof used for sun shading allowed 19% of energy to be saved, typically used for cooling needs [80].

Energy-Efficient Heating, Ventilation, and Air Conditioning (HVAC), Domestic Hot Water, and Lighting

(1) HVAC Systems

Evaporating cooling is a growing technology for providing buildings with cool air, especially efficient in hot and arid climate zones [87]. The technology relies on the use of water to increase air humidity resulting in its temperature reduction and allows saving around 16% of energy compared to conventional air conditioners in very hot climates [87].

Sensible and enthalpy heat recovery systems using heat exchange between cool intake and warm exhausted air streams allow the recovery of 60–95% of wasted energy and provide additional ventilation [80].

Radiant heating and cooling systems are proven to be up to 15–20% more energy-efficient compared to conventional systems [80]. Floor heating systems can be used in cold climates and chilled ceilings in mild and hot locations [80].

Variable-air-volume (VAV) air-conditioning systems demonstrate excellent energy savings of up to 30% compared to conventional systems [88]. Instead of varying intake air temperature, VAV systems control the ratio of intake and exhaust air, which can maintain the desired temperature of the indoor air [80].

(2) Energy-Efficient and Autonomous Lighting

The use of light-emitting diode (LED) lighting, which is up to 80% more efficient than conventional bulbs, is expected to reduce energy consumption by 40% in 2030 [89]. Due to the LED efficiency, they can be widely used for off-grid applications utilizing solar, kinetic, or wind energy [89].

(3) Renewable Energy Generation Systems

Solar, wind, geothermal, and bioenergy are the primary sources that provide buildings with clean, renewable energy [80]. Solar rooftop photovoltaic (PV) panels have a long history of application in residential and commercial construction projects. However, their use can be limited by the roof area, especially for high-rise buildings [80]. The growing building integrated photovoltaic (BIPV) technology helps to solve this problem. PV material can be used for building windows and facades to transform them into electricity generation units, which can also preheat air and water [90].

Although energy harvesting from wind tends to be less predictable than from solar, various wind energy generation units such as building-mounted and small-scale wind turbines proved to provide significant amounts of energy for buildings [80].

Geothermal energy is known as an abundant renewable energy source for heating, cooling, and electric energy generation purposes. It provides a more consistent output than wind or solar systems due to lower dependence on ambient climate conditions [91]. Although the use of geothermal systems for cooling and heating purposes requires high initial investments, their operation cost is very low [78]. Furthermore, combining heating and cooling geothermal systems with other supplementary renewable energy systems such as solar thermal collectors, solar photovoltaics, and cooling towers brings additional benefits. Thus, the increased overall efficiency results in lower upfront and operation costs. Additionally, supplementary renewable energy systems prevent geothermal systems from potential gradual efficiency degradation and ground fouling [78].

Biomass itself is a great source for providing buildings with both electricity and space heating [80]. Several waste-to-energy technologies, such as bio-gasification and anaerobic digestion, allow energy recovery from organic agricultural and food waste [92].

Advancement in building energy efficiency and the extensive use of clean, renewable energy is vital for meeting the energy needs of the growing population. The state-of-the-art building energy consumption reduction strategies and clean, renewable generation technologies provided in this section can not only ensure energy savings but also create a favorable environment for building occupants.

3.3.3. Indoor Air Quality (IAQ)

Importance of IAQ

IAQ is one of the components of Indoor Environmental Quality (IEQ), among others, such as thermal comfort, acoustic quality, and visual comfort, which play a significant role in occupant satisfaction [93]. As mentioned earlier, people spend the majority of their time indoors, and clean air inhaled per capita per day is 10 m³ to 12 m³ [94]. While good IAQ can lead to an increase in occupants' productivity, a poor IAQ can cause sick building syndrome [95], or even death. According to the WHO, 3.8 million early deaths were due to inadequate domestic IAQ, causing nearly 6.8% of worldwide death [96].

Sources of Indoor Air Pollution

Factors such as choice of construction materials, human actions, indoor and outside contaminants, HVAC systems, and some of the building parameters such as volume, area and insulation contribute to poor IAQ [94]. For example, indoor combustion, which is the result of gas stoves or fireplaces, and wood products, can cause significant air pollution [94]. In addition, bacteria grown from wet HVAC surfaces can also cause pollution indoors [97].

IAQ Improvement and Energy Consumption

In order to eliminate IAQ problems, many strategies were put in place, including the development of standards, codes, and guidelines. American Society of Heating and Refrigeration Engineers (ASHRAE) standard 62.1, for instance, was created to ensure acceptable air quality for building dwellers. It was developed as a guideline for all the stakeholders engaged in the HVAC industry as they design, build, install, and maintain systems to ensure acceptable air quality. ASHRAE thermal comfort standards prescribe that thermal comfort is achieved when 80% of the inhabitants express no dissatisfaction with the indoor thermal conditions [98], and outdoor air to air generators for large and small office buildings allow only 5 cfm/person and 4.2 cfm/person, respectively [99]. In addition, ISO 16000-40:2019 [100] was designed to offer air quality guidelines suitable for building users subject to local requirements and limitations.

Furthermore, to identify more sustainable and cost-effective ways to improve the quality of indoor air, many researchers made use of various parameters, namely the concentrations of gaseous pollutants such as Nitrogen dioxide (NO₂), formaldehyde, and Total Volatile Organic Compounds (TVOCs). Other parameters include a period of construction, building location, type of ventilation system, temperature, relative humidity, Air Exchange Rate (AER), type of building (house, office, school, apartment) [97], and indices to assess IAQ in buildings [101]. The Environmental Protection Agency (EPA) also recommended three solutions to enhance IAQ, namely, monitor indoor pollution suppliers, improve the type of ventilation system and use air cleaners [80]. Although implementing these strategies can bring in indoor fresh air [102], it is also critical to consider the consumption of energy for heating and cooling the fresh incoming air [93] as having fresh air can increase energy consumption and cost due to the difference in indoor and outdoor temperature [80]. HVAC systems can consume from 20% to 60% of electricity in a building and to mitigate that, energy-efficient design is recommended, which can be implemented through three strategies, namely system design, control and energy recovery [103].

Solutions for Improved IAQ

Researchers have found technologies and innovations that can help maintain and improve IAQ while reducing energy consumption and cost. Heat recovery ventilators, for example, can be used to generate outside air into the building at a much lesser cost; the optimum ratio of makeup air to recirculation air is another way, as it can reduce nearly 22.1% of energy [80]. Additionally, combining Demand Control Ventilation (DCV) with an economizer substantially improved IAQ, and evidently

saved 88.47% of energy in comparison to the conventional control [104]. Moreover, in an experimental study conducted in Kuwait, the Middle East, researchers used a chilled ceiling and mixed displacement ventilation, also known as CC/DV system, to save energy while still maintaining acceptable air quality. By using the mixed system, the energy consumption reduced by 15% to 20% when compared to the traditional system [105].

3.3.4. Smart Building Monitoring and Controls

Like any other design of a new building, the start of the project begins with an idea. There are different stakeholders who will be involved with the project including the occupants, managers, contractors, designers and the maintenance personnel. Decisions on building operations and implementing smart monitoring and controls should be made early on in the project to accrue the maximum benefits while involving key stakeholders in the discussion. Smart building monitors include IEQ sensors, monitoring devices that can be integrated with the Building Automation System (BAS). The major aspects that will be discussed are smart grids, smart meters and smart home automation systems.

Energy Management

(1) Smart Grids

Smart grids are an automated delivery system for information and energy. The smart power grid uses computers to communicate with buildings and power sources, allowing information regarding power usage to flow from the home's smart meter to a transformer to the power company and back [106]. This helps with load shedding during peak times [106] and allows the power company to monitor energy usage, check for spikes, monitor peak usage times and restore power quicker after a power outage, and allows the integration of renewable energy [107].

Utilizing computers, the smart grid can monitor the system itself. It is able to tell when certain parts of the grid are getting old or no longer efficient. In addition, the computers can reroute power from one source to areas that may have power outages: they are able to detect when important resources such as traffic lights or phone systems are down during an emergency. They can manage power consumption for a home or an entire neighborhood. Demand response is important to support smart grid technology. The authors of [107] described different types of consumers in the demand response environment as those that change their usage during peak hours only, those that do not change their usage patterns, and those that move their peak loads to off-peak hours. While demand response offers several benefits like reducing congestion and GHG emissions [108], consumers may choose to participate either through incentive-based or price-based programs [107].

In addition to monitoring the power grid, smart grids allow the customer to sell or share their overflow back to the power company. Prosumers is a term used for customers who are energy-producing and sharing the excessive energy they generated [55]. Advanced Metering Infrastructure (AMI) connects users and utilities, along with Home Energy Management Systems (HEMS) [55], to monitor consumption patterns. Renewable energy production by consumers can be used as a new source of energy and can be shared with other consumers and the grid [55,107].

The ability of prosumers to interact with smart grids requires a communication network. The infrastructure needed to accomplish this can range from simple to advanced and needs one of the following, i.e., General Packet Radio Service (GPRS), Bluetooth, ZigBee short-range wireless, or even power lines [55]. These connect the smart grid with the home's smart meter.

(2) Smart Meters

Smart meters are advanced meters, which are able to (1) collect data on consumers' electricity usage, (2) communicate these data to other power system participants on the local utility grid, and (3) get pricing information from Distribution System Operators (DSOs) to stop/start household appliances [56].

Smart meters not only measure a consumer's utility usage, but also communicate with a smart grid to transfer information directly to the power company. The consumer knows exactly how much energy is being used. If a consumer generates renewable energy to sell back to the power company, the smart meter knows exactly how much energy is being sold [107]. Integrating a smart home automation system with a smart meter allows for the control of energy usage and can reduce energy waste.

(3) Smart Home Automation

Smart home automation systems have seen increasing adoption in recent years [109]. They require a hub or central controller, a way to control all the devices within a home. There are many different types of home automation or hubs on the market that serve different functions including serving as a security system, and controlling building electrical systems and devices through wireless technologies [109]. They can be controlled with apps on a mobile phone or personal computer (PC). These apps can monitor the smart meters and the information they provide as well as any device that is connected to it. These hubs can completely turn off appliances that are not in use to eliminate usage by "idling". Some of these devices include televisions, gaming consoles, coffee makers, and cable boxes. Even though they are not on they are still using energy. These apps have the ability to turn devices off even when the user is not home and can schedule when appliances turn on and can even lock and unlock doors while away. They provide real-time information on peak energy usage so the user can make informed decisions. While some home automation systems are more for convenience, others can reduce energy use by closing the blinds on sunny days to prevent heat exchange or opening those same blinds on cloudy days, allowing natural sunlight to be used instead of light fixtures. They have sensors and automation to determine when is the best time to open or close based on energy consumption and peak times.

Human Interactions

Technology alone does not guarantee low consumption [50], so "smart" buildings are impossible to achieve without "smart" users. Leaving a room with the TV or computer still powered on—not in use—wastes energy. Data collected from these devices are also beneficial since human behavior and activities impact building energy consumption and indoor environmental conditions [110].

Technology such as apps on phones and devices like "smart" thermostats allows people to adjust the temperature within the home for times when no one is home, and using occupancy sensors and not pre-set times helps to reduce the effect of the human factor [111]. These apps can also alert the end-user to unexpected energy peaks and dips; they provide useful information and feedback to allow the user to make informed decisions.

4. Conclusions

4.1. Waste Management in Buildings

Before physical construction, designers have a decisive role in minimizing construction waste by means of component prefabrication, material standardization and taking advantage of growing BIM technologies. Designing for limited waste is the essential first step towards an effective waste management plan. During construction, builders should be more conscious about material life cycle because doing so can maximize its use, longevity, demand, and cost. The unavailability of sustainable materials, direct and indirect costs, lack of ability to enforce sustainability policies, and lack of experience are some of the most common issues that hinder the implementation of sustainability on a global scale. Reusing and recycling are practical and economical approaches that embrace and encourage sustainability principles in a way that is accessible to all communities and economies.

Water sources need to be secured and better managed worldwide. Buildings play a fundamental role in wastewater reduction and water-saving pursuit. Sustainable building provides tools for stakeholders to improve efficiency and minimize waste and GHG emissions.

4.2. Energy Efficient Operations

A variety of approaches have been presented to tackle building energy consumption, reduce GHG emissions, and reduce waste. Some of these technologies have already proven their effectiveness in practice. As new construction projects incorporate these technologies, their analysis will provide a more accurate estimation of possible energy savings and implementation costs. Building automation along with smart grids and smart meters can improve energy efficiency if used correctly. There are many innovative techniques to aid in energy conservation and cost savings throughout the life of a building. While reducing energy consumption is essential for a sustainable building, the quality of the indoor environment and its effect on building occupants must be considered. IAQ is one component of IEQ that has a major impact on the wellbeing and productivity of building occupants, as a poor IAQ can cause sick building syndrome and reduced productivity. IAQ can be compromised by human activities, indoor and outdoor pollutants, and HVAC systems. Implementing energy-efficient solutions and adhering to existing IAQ standards can lead to acceptable IAQ.

To align all these aforementioned initiatives and technologies while working toward achieving triple-bottom-line sustainability, life cycle impacts should be analyzed to ensure the proposed reduction of CO₂eq is feasible.

4.3. Recommendations and Future Research

High upfront cost, low technology adoption, and local codes and policies, among others, are some of the challenging aspects that sustainable building advocates must holistically consider as the building industry works toward improving waste management practices and promoting energy efficiency for present and future generations. Future research will explore approaches to close the loop through Return on Equity (ROE) assessments, so stakeholders and communities have the right tools for decision-making, to reduce waste and promote sustainable building operation.

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