

## Review

# Technological and Sustainable Perception on the Advancements of Prefabrication in Construction Industry

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**Abstract:** The construction industry has experienced phenomenal growth because of technological advancements in the past couple of decades. Prefabrication constitutes a sizeable share of this industry and is being adopted all over the world. The method of casting construction elements in a controlled environment and assembling them on-site has revolutionised the industry. Research on various aspects of the technology is ongoing around the world, and an impressive number of articles have been published. However, the prefabrication technology, materials used, and terminology have varied across locations, which may have hindered the method's wider acceptability. By evaluating technical articles published between 1991 and 2022, this report analyses the present body of knowledge regarding prefabrication technology, its evolution, sustainability, and stakeholder views. This technology effectively contributes around 40% in time saving, 27% in cost reduction, 30% in reduced carbon emissions, and 84% in on-site wastage reduction. It also increases quality, gives a dependable alternative for meeting mass construction targets, is energy efficient, and provides environmentally conscious options. This paper contributes to the body of knowledge by providing a snapshot of the prefabrication industry spanning three decades, detailing a wide range of factors affecting the industry.

**Keywords:** prefabrication; sustainability; materials; technology



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## 1. Introduction

In recent times, the world has been advancing rapidly in terms of technology adoption and development. However, many construction activities are still slow-paced as they are based on conventional and outdated technology. The differences between construction and other fields imply that there exists a broad scope for upgrading construction methods. Prefabrication, also known as prefabrication, is one such approach that can enhance current construction practices. Prefabrication made a mark in low-cost mass housing projects and emerged with better time control, cost savings, enhanced quality, increased productivity, and safety. The recent developments in prefabrication also look into the economic affordability of single units and environmental sustainability.

Prefabrication can be defined as the manufacturing process of the building components either in factories or temporary plants and then transporting them for installation at the site. This technology made its debut around the mid-1880s and grew in demand during World War II. Countries with a smaller workforce and more manufacturing industries have adapted this prefabrication technology over traditional construction practices. Countries with cold climates have also leaned into this technology because of the less available outdoor working time. Sweden has an efficient record of 84% of the construction being prefabricated [1]. Moreover, many economically advanced nations such as the USA, The Netherlands, Germany, the UK, Portugal, and Japan have succeeded in executing this prefabrication technology in their construction industries [1–3].

The generation of agricultural, industrial, and construction waste has escalated a need for sustainability in the construction process to balance the ecological cycle. This need is reflected in the sustainable development goals (SDG 11) drafted by the United Nations [4]. Sustainable construction can be defined as “the creation and responsible management of a healthy built environment based on resource efficient and ecological principles” [5]. According to a prediction by the United Nations, urbanisation of developing and developed countries will be around 64.1% and 85.9%, respectively, by 2050 [6]. As per this prediction, mass housing projects are required in urban areas. Financial, durational, and resource constraints in these projects have opened the doors for prefabrication, which is efficient in making these constructions affordable.

Many case studies have concluded that the implementation of prefabrication has resulted in efficient execution and quality control. It has reduced material waste, energy usage, carbon footprint, operational impact, and disturbance to the surrounding environment. Conversely, it has improved working conditions and offered time and cost savings.

In this study, we aimed to capture the overall advancements in technology that allowed prefabrication to emerge as an energy-efficient, sustainable, and green technology. Therefore, this paper gives a review of various articles from the early 1990s over three decades. This paper also includes a discussion about the evolution of the technology, materials used, precast elements involved, performance related to the end product’s properties and energy, and stakeholder views for implementing this technology.

## 2. Methodology

The current study consulted documents retrieved from Google, Google Scholar, Science Direct, Web of Science, Research Gate, and Scopus databases. The terms used for collecting the literature from the search engines include prefabrication, prefabricated housing, prefabricated structure, modular building, industrialised building, comparison between modular and traditional buildings, and a few other related searches. Literature published in the past three decades, i.e., from 1991 to 2022, was collected from major journals such as *PCI Journal*, *Energy and Buildings*, *Building and Environment*, *Construction and Building Materials*, *Automation in Construction*, and *Sustainability*. Publications from engineering publishers such as Elsevier, Springer, MDPI, and Wiley, in addition to engineering conference proceedings and webpages, were also included in this research. The papers reviewed in this research covered a broad spectrum of domains ranging from construction technology, civil engineering, environmental engineering, manufacturing, multi-disciplinary areas, environmental sciences, sustainability, and management to urban studies. Data collected from Web of Science were analysed and a bar graph was plotted that shows the distribution of publications found between 2002 and 2021 (Figure 1). A drastic increase in the published articles over the past four years represents increased research interest in related areas. Data regarding various publications that contain the mentioned terminology were collected, analysed, and presented in Table 1.

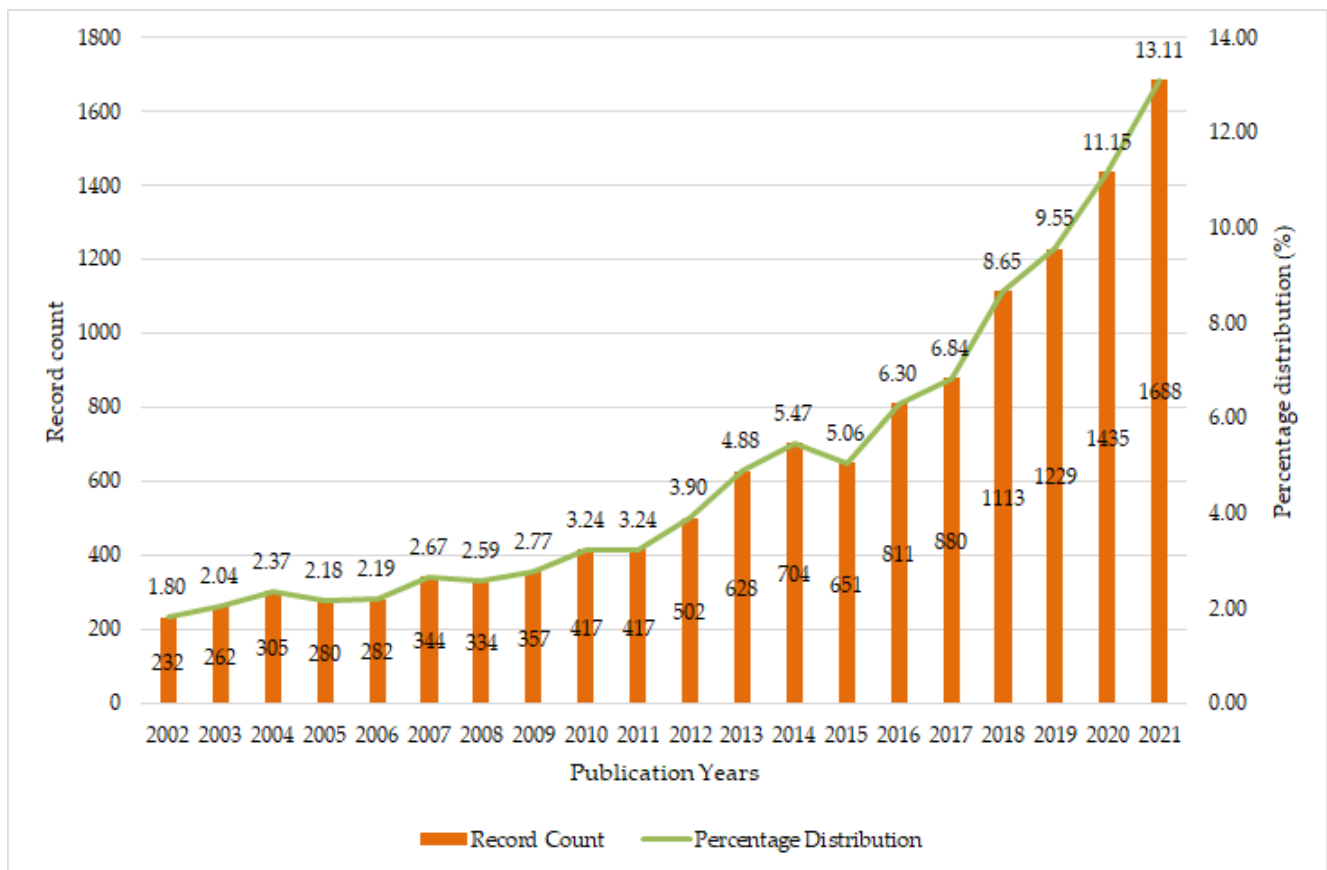


Figure 1. Bar graph showing frequency of publications from 2002 to 2021.

Table 1. Percentage distribution of prefab publications according to publishers.

S. No.	Publishers	Percentage Distribution (%)
1	Elsevier	26.26
2	Springer Nature	8.33
3	Wiley	6.76
4	ASCE-Amer Soc Civil Engineers	5.24
5	Precast/Prestressed Concrete Inst	4.73
6	IEEE	4.38
7	MDPI	4.30
8	Amer Chemical Soc	3.96
9	Taylor & Francis	3.51
10	Ernst & Sohn	2.03
11	Sage	1.96
12	Royal Soc Chemistry	1.59
13	Techno-Press	1.34
14	Amer Concrete Inst	1.11
15	Oxford Univ Press	1.10
16	Ice Publishing	1.07
17	Hindawi Publishing Group	1.06
18	IOP Publishing Ltd.	0.88
19	Lippincott Williams & Wilkins	0.79
20	Emerald Group Publishing	0.68
	Others	18.93

The benefits of prefabrication have earned it global acceptance. The number of publications originating from various countries is displayed in Table 2. China and the USA lead the publication tally with more than 34% of the overall publications. The top five countries,

namely China, the USA, Germany, England, and Australia, contribute almost 51% of the total publications in this area. India's contribution is 1.5% of the total publications.

**Table 2.** Percentage contribution of various countries to research on prefab.

S. No.	Countries/Regions	Percentage Contribution (%)
1	Peoples R China	17.56
2	USA	17.08
3	Germany	7.67
4	England	5.13
5	Australia	4.13
6	Italy	4.02
7	Spain	3.29
8	Canada	3.15
9	France	2.67
10	South Korea	2.38
11	Switzerland	2.27
12	Japan	2.15
13	The Netherlands	1.94
14	Brazil	1.63
15	Turkey	1.60
16	India	1.49
17	Sweden	1.25
18	Poland	1.13
19	Belgium	1.00
20	Singapore	0.98
	Others	17.48

A total of 119 articles were collected for this study based on the abstract review. A detailed review was then conducted, and 98 of the collected articles suited the study's scope and are thus presented in this review. The information collected from the literature was segregated according to the aim and objectives of the journal/article. Then, it was sorted based on the year of publishing, the need for prefab, its advancement over the years, advantages, and challenges of the technology. Different perceptions of prefab's growth regarding materials, technology, sustainability, performance, and stakeholders' views were identified and briefed accordingly.

### 3. Terminology

Construction-related terms are often mistaken due to minor differences in practices and a lack of globally accepted standards. Some of the terms relevant to this research are precast, prefabrication, modular, panelised, and manufactured housing. These terms are discussed in the following paragraphs.

The term precast is commonly used for elements made of concrete. The “pre-” in the term refers to preparing an element before its final installation. Precast made its way into the construction industry with the manufacture of railway sleepers in the 1950s [7]. For other applications besides railways, concrete is cast into reusable moulds and forms as required for a column, beam, slab, or a wall. The set concrete is removed from the moulds, cured, and stacked before it is finally utilised.

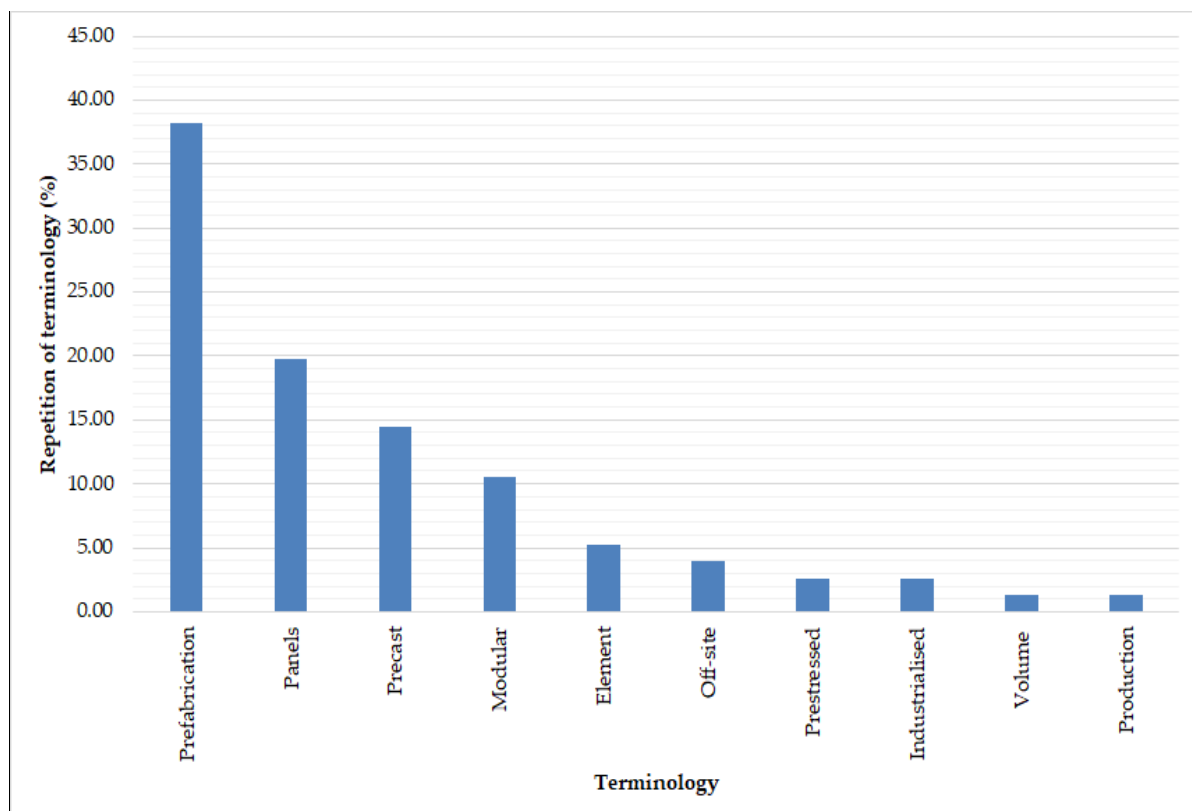
Prefabrication, on the other hand, consists of assembling structures such as buildings, bridges, and offshore platforms by using factory-made precast elements such as beams, columns, slab panels, and wall panels [8]. The process involves manufacturing components off-site and then transporting them to be installed on-site. Terms such as panelised, modular, manufactured, readymade, production homes, off-site buildings, industrialised building system, and others relate to prefabrication [9–13].

Prefab can be categorised mainly into panelised, modular, and manufactured methods [14]. Panelised housing refers to houses built with the wall and slab panels manufactured in a controlled environment, transported to the site, and positioned on the

foundation [15]. This can also be referred to as element prefabrication [16]. Modular buildings involve box-like modules similar to partially built homes. These modules are built in factories under a controlled environment [12] and generally include a four-walled room or unit with or without the slab, which is transported and installed on-site. These modular housings are also known as volume prefabrication [11]. A major difference between these two methods is that the panelised elements are two-dimensional, whereas the modular parts are three-dimensional modules with roof and external finishes [17,18].

Besides the methods mentioned above, another method exists wherein a complete house is manufactured in a factory, with all services such as electrical, plumbing, and others installed before its transportation and installation on the on-site foundation. This is termed manufactured housing or unitised whole building [14,17].

In this present collection of literature, many of these terms have been repeated over a variety of journals. The majority of the repetitions include prefabrication, followed by panels and precast. These repetitions that are part of the literature are put into a graph, as shown in Figure 2. The figure suggests that prefabrication is the key term used by the majority of the authors, and many other terms fall into the aegis of prefabrication.



**Figure 2.** Percentage repetitions of the terminology used in the review articles.

#### 4. Prefabrication over the Past 30 Years

Prefabrication is a well-established method that is widely accepted and executed across many countries around the globe. Much work goes into prefabrication projects that span across several project phases. Some of the most unique and important aspects are acquiring raw materials, manufacturing, transporting, and installing prefabricated elements on a site. Post-occupancy, the study of the on-site performance of end products, validates the achievement of the expected design objectives, furthering the development of the project processes, and also helps identify research voids that must be filled. Technology has a way of expanding as it upgrades itself by virtue of growth in research and development areas. There is an ever-growing demand for the adaptation of new technologies in the prefab

industry. Many stakeholders such as the clients, contractors, industry practitioners (e.g., architects/designers), and end-users are involved in this process, and it is important to consider their perspectives. This manuscript deals with studying many of these factors in the evolution and sustenance of prefabricated technology.

#### 4.1. Material Adaptation in Prefabrication

Traditional construction methods involve materials such as timber, concrete, steel, and clay. During the initial years of prefabrication, timber had a major role, but later, steel and concrete were incorporated into prefabricated designs [19]. With an increased focus on sustainability in construction, the prefabrication industry has replaced traditional materials with agro-industrial by-products. The increased carbon footprints, higher energy consumption during manufacturing processes, and transportation challenges accompanying the exploitation of natural resources led to greener/sustainable alternatives to replace traditionally used prefabricated materials [20]. The utilisation of locally available raw materials has also ensured better performance and a reduction in construction costs [21]. Moreover, cement is an energy-intensive construction material, has significant usage in traditional concrete and other construction products, and is also responsible for about 7–8% of total CO<sub>2</sub> emissions [22–24]. Hence, a paradigm shift towards using materials such as fly ash, rice husk ash, silica fume, ground granulated blast furnace slag (GGBFS), geopolymers activated with other bio-ashes, and other similar materials has been observed over the past few decades [7,25–30]. The replacement of naturally available aggregates with crushed aggregates, industrial by-products, construction and demolition (C&D) waste, and recycled concrete aggregates was found to be efficient in a sustainable approach [7,21,31,32].

Prefabrication, a factory-based process, offers the flexibility of choosing raw materials, whether from locally available natural sources or manufactured sources. The flexibility has resulted in cost-effective and energy-efficient end products. Further research into the development of such designs has yielded the idea of precast concrete sandwich panels [26] and precast large construction panel (PLCP) [20] systems. These were developed with an insulating member sandwiched between two layers of concrete, often called concrete wythes, connected with the help of mechanical connectors.

Portland cement concrete, foamed concrete (FC), ultra-high-performance concrete (UHPC), textile-reinforced concrete (TRC), and fibre-reinforced concrete (FRC) have all been tested as concrete panels [26–29]. Adding to this list are high-performance fibre-reinforced concrete (HPFRC), ultra-high-performance fibre-reinforced concrete (UHPFRC), and self-compacting concrete (SCC). Other novel enhancements include using high-density geopolymer (HDG) in concrete sections and light gauge steel-framed structure (LGSFS) in steel sections [20,30,31,33,34].

Insulating materials act as the media of thermal resistance, and the materials used for this purpose are expanded polystyrene (EPS), polyurethane (PUR), polyisocyanurate (PIR), extruded polystyrene (XPS), vacuum-insulated panel (VIP), and several others [26,35,36]. Reinforcements such as steel, glass mesh, bamboo, carbon textile, polypropylene fibres (PF), and glass fibre-reinforced polymer (GFRP) bars have been used for making the prefabricated panels [37–40]. These unique materials which provide alternatives to conventional concrete are summarised in Table 3.

**Table 3.** Variety of materials used in prefabrication over the years.

Concrete	Cementitious	Aggregates	Reinforcement/Connectors	Insulation
		Timber [16,41] Steel [42]		
TRC [33,43–45]	Fly ash [25,27,29,37,46]	Crushed sand [7]	Steel fibres [25,36,47,48]	EPS [30,34–36,39,44,49–53]
UHPFRC [33]	GGBFS [7,34]	Mangalore tiles and coconut shells [21]	Glass fibres [50]	XPS [36,51]
TRRPC [38]	Silica fume [49]	FGD gypsum [28]	FRP—glass, carbon, and basalt [33,36,39,43,45,51]	PUR [33,35]
UHPC [49]	Alkali activation [7,25,29,46]	C & D waste, rubble [31]	Poly propylene fibres [38]	PIR, VIP [35]
HPFRC [30]		Recycled concrete aggregate [32]	Welded wire mesh [53,54]	Mineral wool [50]
HDG [31]			Bamboo [37]	MgO boards [11]
SCC [34]			Alkali-resistant glass [33,44,52]	FC [38,55]
LGSFS, PLCP [20]				

As fly ash is widely available across the globe, its involvement in mix designs has helped cement usage reduction as well as the enhancement of material properties. Many of the old structures have reached their service life and their demolition is necessary. Increased waste from demolition is a challenge to manage and dispose. Advancements in construction have enabled the utilisation of many alternate raw materials as mentioned in the earlier literature. Lean technologies and the need for energy-efficient construction practices have led to panelised prefabrication systems with the application of insulation materials. Utilising the locally available natural and alternate raw materials proved their significance in cost reduction and environmental safety.

#### 4.2. The Basic Building Blocks of Prefab

Prefabrication is a reliable and cost-efficient alternative to traditional construction practices. It was first implemented as precast railway sleepers in the late 19th century but rose to prominence during World War II due to its ability to expedite construction. The war served as a catalyst that led inventors to expand the knowledge base of prefab, and the prefab industry grew from the simplistic size-constrained railway sleepers to design-friendly complex construction components. Gradual advancements over the years led to small-scale beams, columns, slabs, mid-scaled walls, roof panels, modular rooms, and eventually to full-scale houses. Prefabrication has proven useful for framed structures, where structures are made of either homogenous or composite elements, and for load-bearing structures such as panelised and modular buildings [56,57].

The concept of maintaining thermal comfort inside buildings has resulted in the insertion of insulating materials into the conventional building components. Such advancement brought in the production of precast concrete sandwich panels, where an insulating sheet is inserted between two precast concrete wythes and connected through connectors [26,30,33,35,43]. The introduction of insulating material in precast walls, roofs, and floor panels was achieved using materials such as magnesium oxide (MgO) boards, orthotropic shell components, and plasterboard, along with concrete [11,41]. Bonding between concrete wythes and insulating layers was achieved by inserting mechanical connectors, applying epoxy, or using an in-pressure casting technique [43,51,52].

The precast approach is used even for the smallest of the components, such as cover blocks, and non-structural elements, such as door and window frames [21]. The precast



panels are also being used as building envelopes, such as façade panels, which increase both aesthetic value and energy efficiency of structures [38,50]. Apart from the major elements used in buildings, there are specific components such as the embedded parts, polyethylene plastic strips, and waterproof plastic, which are helpful during assembly, achieved through innovation in precast technology [10]. In summary, whatever level of complexity was expected, the prefabrication industry achieved it in time by adapting and innovating to meet the changing needs. Moreover, most of the prefabrication included wall panels either structurally placed or as sandwich panels.

#### 4.3. Performance

Various combinations of materials were trialled over the years to manufacture prefabricated elements. The aim was to achieve better properties compared to traditional construction products and components. Some of the properties are discussed in the following sections.

##### 4.3.1. Mechanical Performance

With the increasing demand for longer spans, high-rise buildings, and larger structures, the major governing factor in concrete's performance lies between compressive strength and density among the other mechanical properties [47]. Similar expectations exist for prefabricated elements. The majority of the studies in prefabricated construction have been conducted to determine the compressive strength of various prefabricated elements. A significant improvement was observed in prefabricated elements wherein the compressive strength of high- and ultra-high-performance concrete reached up to 193 MPa [26,30,33,49,53]. In comparison, the conventional concrete reaches only up to 20 MPa. Figure 3 shows the variation in compression strength starting from 6.6 MPa to 193 MPa studied in this review.

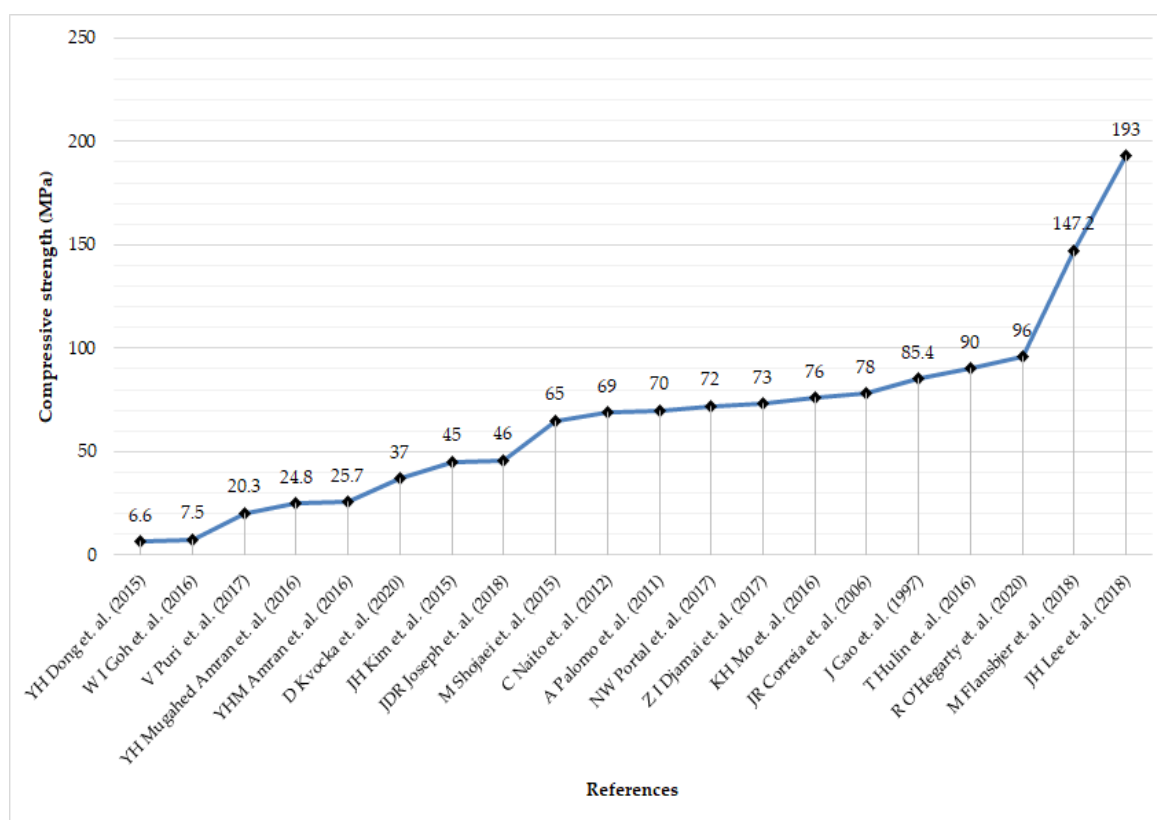
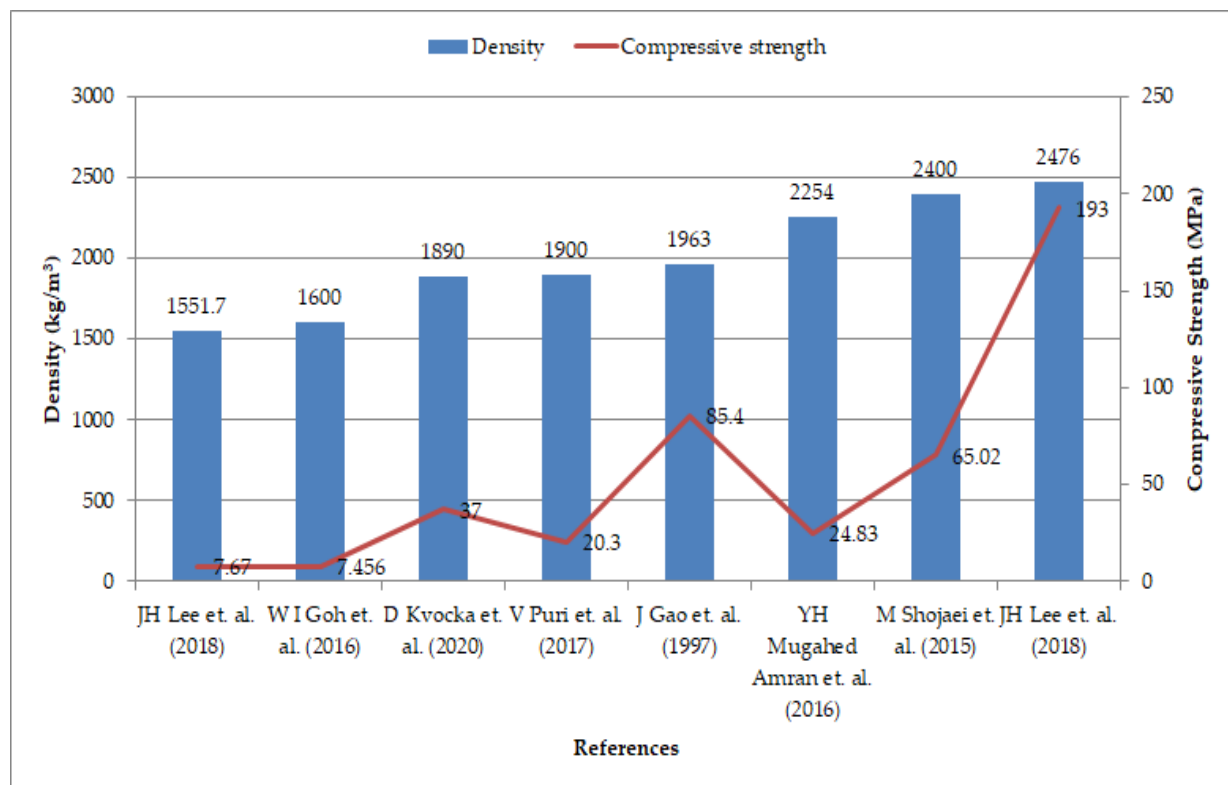


Figure 3. Compressive strength in the presented literature.

With the focus of reducing dead loads, several attempts have been made to develop lightweight concrete by using various foaming agents and inserting insulating materials



as a sandwich layer between two concrete wythes [49,55]. The density of concrete was brought down to a minimum of  $801 \text{ kg/m}^3$  when compared to a density of  $2400 \text{ kg/m}^3$  for conventional and high-performance concretes. It was even brought down to  $200\text{--}300 \text{ kg/m}^3$  for use as an insulation material [43]. A graph showing the relationship between density and compressive strength is plotted in Figure 4. Based on the literature review, many researchers have attempted to achieve high strength for low-density products. However, it is evident that high-density concrete produces high strength.



**Figure 4.** Density and compressive strength in the presented literature.

Apart from these, other mechanical properties such as flexural and tensile strength were tested in many studies, yielding better results for their respective panels [33,34,49,53]. There was a gradual increase in tensile strength from  $0.24 \text{ MPa}$  to  $9.8 \text{ MPa}$  (see Figure 5). However, in one particular study, an increase in the tensile strength to more than 300% was observed with the addition of UHPFRC. These mechanical properties determine if the panels will be load-bearing or non-load bearing.

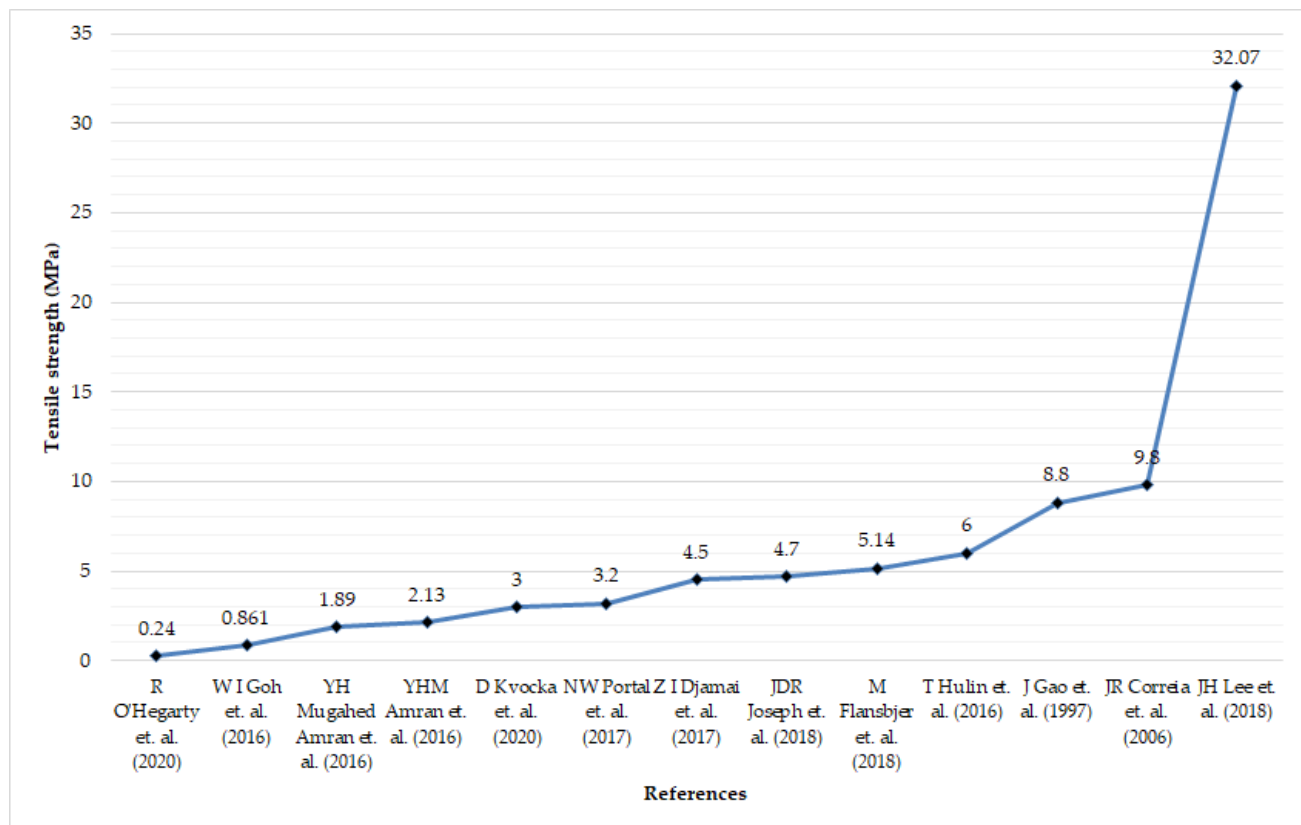


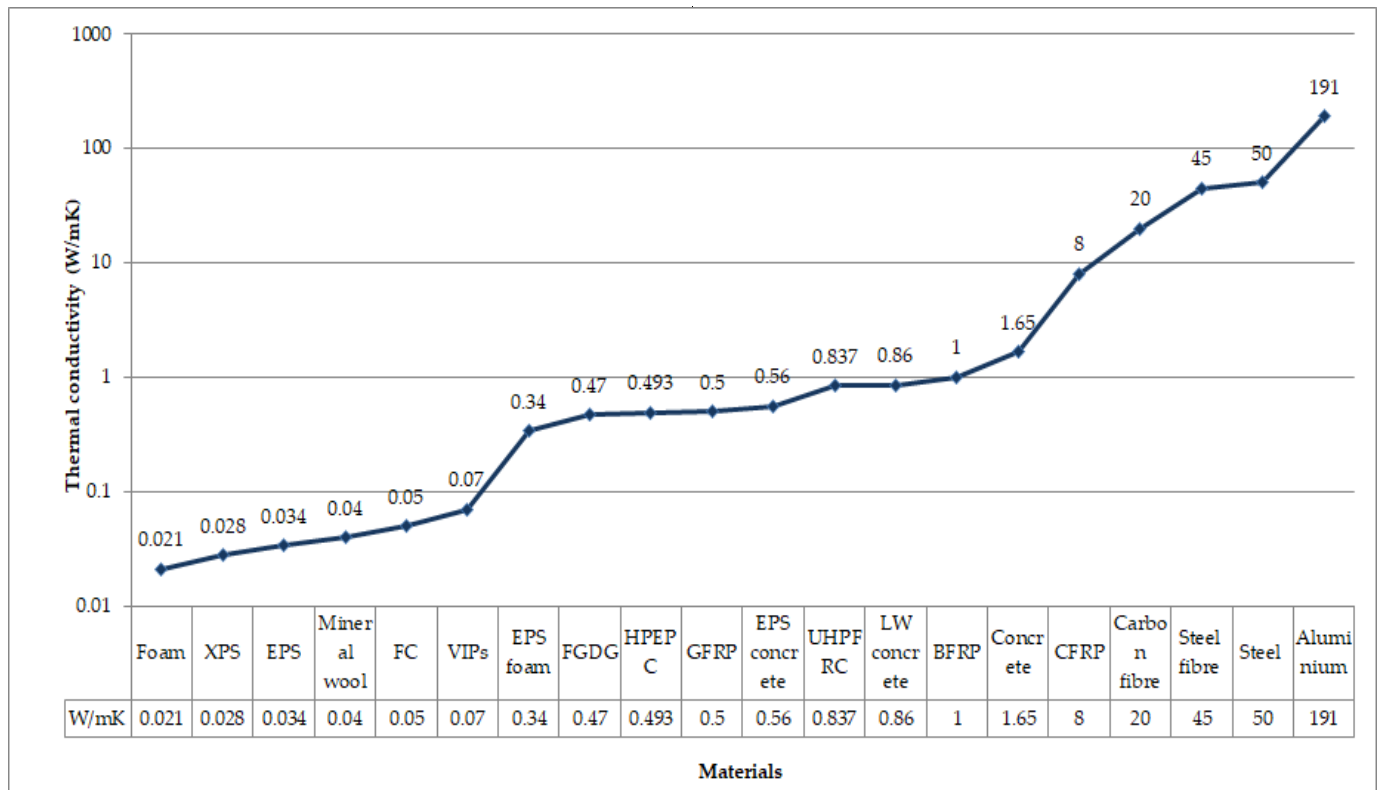
Figure 5. Tensile strength in the presented literature.

The mechanical properties of the building elements are hindered by the natural deterioration during their service life. Various aspects such as weathering, aging, and other chemical attacks play a crucial role in this hindrance. Durability is one such criteria that is evaluated for materials and end products to determine the effect of these aspects on the material properties. Water absorption, carbonation resistance, chloride penetration, freeze-thaw tests, and ultraviolet (UV) tests are some of the methods performed to determine durability [58,59]. Along with these, various other Fourier transform infrared spectroscopy analyses were performed in earlier research studies to understand the aging process of the material [59–61]. Hence, the investigation of the durability parameters addresses the issues related to long-term sustenance of the structure by maintaining the designed mechanical properties.

#### 4.3.2. Thermal Performance

Extreme climate has been forcing people to stay indoors within a controlled environment in a thermal comfort range. The concept of indoor environment quality (IEQ) has come into existence and is achieved through controlled indoor air quality (IAQ), temperature, humidity, lighting, and noise [5]. From the perspective of building physics, the prefabricated elements minimise thermal conductivity primarily because of the presence of non-conductive composite elements, resulting in occupants' comfort [14]. The literature review shows that the thermal conductivity of various materials used in the traditional construction industry has been studied, and materials with the least thermal conductivity/transmittance were selected for experimental trials [28,48,62]. Various insulation materials were considered, which have U-values ranging from 0.08 to 3.55 W/m<sup>2</sup>-K [26]. Low U-values indicate better insulating performance. For prefabricated construction, insulating materials such as EPS, XPS, and PUR were used between concrete panels, and better results were obtained because of low thermal conductivity [35]. Figure 6 lists various types of materials in the construction industry with their thermal conductivities. Although other insulation materials have better

thermal properties and strength, researchers have opted for EPS because of its greater availability, lesser density, and lower cost.



**Figure 6.** Thermal conductivities in the presented literature.

#### 4.3.3. Life Cycle Assessment (LCA)

Life cycle assessment (LCA) is a sustainability concept that conveys the environmental impacts related to the different phases of a product's life cycle. This could involve either cradle-to-grave or cradle-to-gate phases of a product, including but not limited to raw material extraction, material processing, transportation, product manufacturing, usage, repair and maintenance, and finally, product re-use, recycling, or final disposal [63,64].

The major LCA phases in prefabrication include securing material, transportation, construction, operation, and recycling. First, the material is secured, which includes extracting, cleaning, sorting, and storing. The material is then precast or prefabricated for later use. The prefabs are then transported for installation, along with other equipment and necessary resources. The structure with prefabs is commissioned and undergoes maintenance due to wear and tear. At the end of the structure's life, the prefab elements are demolished and recycled or managed through local waste management guidelines [53]. Material weight, energy, emissions, toxicities, water, solid waste, and percentage usage of recycled and recyclable materials are all considered in the analysis. LCA modelling is a crucial task where data are collected from many industry stakeholders, which requires significant time and effort [54]. For this current research, data about LCA were collected from the reviewed literature, and various impact-measuring indices are presented in Table 4.

**Table 4.** List of impact measures considered in LCA.

S. No.	Impact Measures	Units	References		
			[65]	[66]	[31]
1	Global Warming Potential	kg CO <sub>2</sub> eq.	✓	✓	✓
2	Acidification Potential	kg SO <sub>2</sub> eq./ kg Mol H+	✓	✓	✓
3	Human Health Effect	kg PM2.5 eq.	✓		
4	Eutrophication Potential	kg N eq./kg PO <sub>4</sub> <sup>−3</sup> eq.	✓	✓	✓
5	Ozone Depletion Potential	kg CFC11 eq./ kg R11 eq.	✓	✓	✓
6	Smog Potential	kg O <sub>3</sub> eq./kg NO <sub>x</sub> eq.	✓	✓	
7	Fossil Fuel consumption	MJ	✓		
8	Eco-Toxicity Effect	mg/kg 2,4-D eq.	✓	✓	
9	Carcinogenic	g benzene eq.		✓	
10	Non-Cancer	kg toluene eq.		✓	
11	Criteria Pollutants	10 <sup>−6</sup> DALYs		✓	
12	Water	1000 L		✓	
13	Human Toxicity Potential	kg DCB eq.			✓
14	Photochemical Ozone Potential Creation	kg Ethene eq.			✓
15	Freshwater Aquatic Ecotoxicity Potential	kg DCB eq.			✓
16	Marine Aquatic ETP	kg DCB eq.			✓
17	Terrestrial ETP	kg DCB eq.			✓
18	Abiotic Depletion (Elements)	kg Sb eq.			✓
19	Abiotic Depletion (Fossils)	MJ			✓

The product phase in the life cycle is critical because it contributes the most to the environmental footprint. This phase generates heat during material production while consuming both electricity and fuel [31]. Cement production, for example, generates heat while consuming electricity and fuel, which is responsible for around 7% of the world's carbon emissions [7,29]. Thus, finding alternatives such as recycled materials (which reduces carbon emissions by up to 20%), alkali-activated materials, TRC, and others are more environmentally friendly than the conventional concrete consisting of virgin materials [21,31,45]. The precast and prefabrication techniques are also effective in reducing carbon emissions by 10% per m<sup>3</sup> and reducing wastage by about 84% [67,68].

Conventional construction contributes 24% of greenhouse gas emissions and 40% of energy use [69]. However, prefabricated constructions were proved to consume less energy, produce less wastage, and emit fewer emissions when compared to conventional methods during the construction and end-of-life stages [42,66]. The carbon emissions are further discerned to decrease with the increase in the prefabrication rate [70]. The concept of net-zero energy building (nZEB) also includes prefabricated elements whose ultimate aim is to create an energy-efficient building where net energy flowing to/from a building sums to zero [69]. The factors responsible for making construction environmentally friendly are choosing optimal designs, decreasing material and labour transportation, and increasing modular construction [65]. Some studies also proved that the construction involving recycled and geopolymeric materials has less of an impact on the environment [31,45].

#### 4.4. Technology

Initially, precast yards focused on simple elements such as railway sleepers. As the technology advanced, they have extended their manufacturing to a variety of other precast elements such as columns, beams, slabs, wall panels, façades, and staircases. Moreover, the technological advancements led to significant cost reductions. For instance, cost reductions of 25% are expected while using filler slabs, 20–30% while reusing waste materials, 40% when using wall panels over brick walls, and around 7% by implementing modular over structural insulated panels [11,21,37].

Off-site prefabrication has seen tremendous enhancements in mechanisation, along with adaptation to advances in automation, simulation, robotics, and reproduction [19,71,72]. These have increased the efficiencies of mechanical and automated processes, virtually eliminating the need for direct human interaction. The processes are also found to be 27% economical while implementing them. Technological advancements have improved efficiencies and minimised waste, playing a vital role in their widespread acceptance throughout the prefab industry. Reduced construction time, better quality control, preferable durability standards, and reduced on-site disruption are found beneficial, whereas shortages of specialised manpower, restricted transport, and limited design flexibility have hindered its growth [73].

Over the past decade, Building Information Modelling (BIM) has proven to be an efficient digitising platform for creating, storing, accessing, communicating, and presenting information about construction projects. Furthermore, BIM is identified as a valued process involving multi-disciplinary coordination and integration of activities throughout the life cycle of the building and its components [74,75]. The literature review shows that projects' pre-construction, construction, and post-construction phases benefit from BIM, where precast elements and structures are digitally virtualised, reducing design costs by up to 30% [76,77]. A rapid increase in Internet of Things (IoT) applications coupled with BIM has also helped improve the operations involving prefabricated elements [61]. This combination of IoT and BIM additionally helps in evaluating the structure during its service life phase through sensors, data acquisition, damage detection, and modelling systems [78].

#### 4.5. Stakeholder Views

Stakeholders who either affect or are affected by the construction industry or prefab industry are owners, clients, users, contractors, designers, supervisors, manufacturers, engineers, and policy makers [16,79,80]. There is a need for these stakeholders to comprehend the gaps and failures of the process and try to use their knowledge to make it adaptable. Proper codes, policies, regulations, and laws regarding the processes must be developed by certain stakeholders such as politicians, city authorities, and engineers who can manage certain risks [81]. Current industry practitioners are ready to take up the advancements in the construction industry, whether from a material or technology perspective [82]. Moreover, some stakeholders have mentioned a lack of scientific studies that enable justifying the selection of prefab versus conventional construction approaches [10]. With the increasing technological advancements, there is a need for stakeholders to familiarise themselves with the rising concerns regarding global warming and greenhouse gas emissions and work towards developing necessary regulations and policies for their control [68,83]. Their perception, strategic objectives, and implementation policies are observed as some of the major factors in setting up a prefab manufacturing unit [84].

Social housing mainly depends on income level, size of dwelling, and affordability [21]. As prefab technology covers these parameters, several stakeholders have adopted this technology for low-cost housing. Additionally, many value-enhancing parameters such as durability, safety, aesthetics, environmental aspects, and profitability are considered while opting for prefab [16]. The technology is around 40% more time-efficient, has better thermal and energy efficiency, and offers greater quality control [66,85–87]. Considering stakeholder demands regarding real-time monitoring of on-site assembly, advancements such as smart construction objects have been achieved using sensors and BIM [76]. Regardless of these gains, stakeholders usually prefer traditional methods over prefab technology mainly because of a conservative mindset towards the need for higher installation precision, costlier technology, and the inability to determine the benefits to the project [88–90].

## 5. Challenges and Future Opportunities

### 5.1. Challenges

The biggest challenge for the prefab industry is the rapidly updating technology. In this digital world, advancements in automation and robotics have been increasing the need

for prefab technology to adapt [91]. Prefab is the preferred solution for social housing, but is unfortunately perceived to be a low-quality solution. Thus, the current market equilibrium sets prefab housing for the mass production market with boxy and non-customisable designs having no variety. Researchers have also listed several misconceptions regarding prefab technology that have become challenging to overcome [92,93]. Lastly, a lack of awareness among stakeholders regarding the core benefits of this technology, policies of financial institutions, and risks in adaptation also pose some of the challenges hindering the widespread acceptance of prefab technology [86].

## 5.2. Future Opportunities

Government agencies in developing countries face an uphill battle of meeting a rapidly increasing housing demand. For example, in India, an increase in urban population combined with limited land for new construction has skyrocketed the demand for housing. The demand has increased exponentially in the past few decades. The Indian government has been taking the required actions to build affordable houses quickly, aiming to construct 8000 housing units per day under the “Housing For All” scheme [94]. Understandably, developing countries are opting for prefab construction, but developed countries are also using prefab to meet their housing demands. For example, homelessness is an unwanted situation major cities are facing across the U.S. [95]. The situation is catching the attention of businesses and has led to the development of modular construction companies [96].

Besides the normal construction times that support prefab construction for the Indian market, the instabilities triggered by the pandemic are also indicating a drift favouring prefab construction. According to current market situations, global supply chain issues and labour shortages are slowing down the Indian construction industry [97]. Similar challenges are faced even in developed countries around the world. Geopolitical situations, market instabilities, and the slow recovery from COVID-19 indicate that the construction industry is going to face these challenges for quite some time. The prefab industry is better structured to absorb the supply chain and labour shortage impacts because of its set-up being that of the manufacturing industry. The prefab industry can support the construction industry by mass-producing building parts and storing them in larger capacities.

Prefabrication offers many advantages and thus gives us confidence that it has better prospects in future mass housing projects. Some findings have highlighted gaps in designs and decision support tools that can help achieve high- performance, sustainable, and affordable housing [86]. The documented advantages of the prefab industry have increased the demand for prefabrication and have ultimately resulted in exploring optimal solutions that enable selecting precast elements and locating them. The advancements have even opened avenues for using artificial intelligence in prefab technology [98].

## 6. Conclusions

Although prefab technology came into existence in the late 19th century, its popularity spiked in the mid-20th century. Over the years, there have been many advancements in technology, particularly in the past three decades. We reviewed and analysed studies published in the past three decades and converted our findings into graphs and tables. A sharp increase in research interest and development has been visible since 2018, mainly in five nations. Four of these five nations are developed countries recognised as leaders in research, technology, and development. While prefab is tagged as a low-cost alternative having low quality, the evidence showing developed countries’ significant interest in prefab gives us reason to believe that the prefab industry has the potential to capture a larger and more respectable market share. With prefab being a low-cost alternative, many developing countries could benefit from the rapidly evolving industry. For example, countries such as India are expected to benefit from the advancements in the prefab industry. They may soon show evidence of higher levels of adoption of, interest in, and research on prefab technology through government-led initiatives.



More than 80 articles from journals, conferences, symposiums, government guidelines, and online articles were analysed in this study, covering the prefabricated industry in more than ten countries. The terminology used in those countries is differentiated and described to enable readers to understand the research topic. We observed the development of the precast industry, starting from manufacturing of small-scaled railway sleepers to meeting the needs of large-scale, fully operational modular houses. This study provides an overview of insights gained about the prefabricated industry, focusing on materials, properties, sustainability, technology, performance, and stakeholders' views. The application of alternate materials such as locally available agricultural and industrial by-products into the prefabricated elements have enhanced its benefits. The developed prefabricated technology is about 40% more time-saving, 27% more economical, and 84% more efficient in reducing on-site wastage than the traditional construction techniques. The present global prefabricated industry has updated itself to match the pace of dynamically evolving technology. The industry has also included high-performance materials, which have benefited it in mechanical, thermal, and environmental aspects. In the energy and thermal domains, utilisation of the EPS in the panels as insulation material has achieved energy efficiency and low density targets. Moreover, this technology is found to reduce carbon emissions by around 30% from the life cycle analysis. Stakeholders' views regarding the selection of prefabricated over the traditional methods, with consideration of pros and cons, have also been discussed in this paper.

On a concluding note, prefabricated technology is still evolving because of the constant technological upgrades around the world, making its adaptability a challenge. Inclusion of sustainability and energy parameters have made it a suitable alternative to the current traditional construction practices for mass housing. Overall, this technology provides opportunities for advancement, and there is considerable potential to bridge the research gaps.

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