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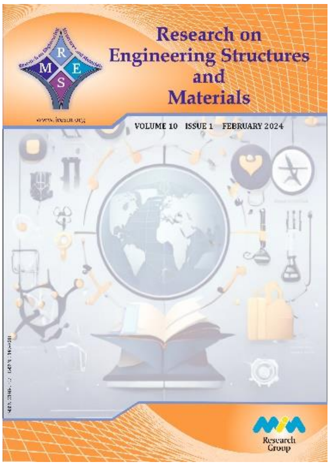

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Review Article

Carbon nanotubes: revolutionizing construction materials for a sustainable future: A review

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Abstract

This review article explores the use of carbon nanotubes (CNTs) as material enhancers in construction and their advantages. It emphasizes ongoing research to gather accurate data on CNT-enhanced material properties and their role in creating more efficient and stronger building materials. The various methods of obtaining and incorporating CNTs into building materials, including chemical vapor deposition and electric arc synthesis, are discussed. A comparative analysis of building materials with and without CNTs is presented to examine their characteristics. The article also discusses future prospects for CNTs in various industries. The study aims to investigate experimental methods for obtaining CNTs, their properties, and their introduction into building materials. The research methodology involves studying literature sources, analyzing experimental results, and examining the structural, mechanical, and electronic properties of CNTs. Analytical methods based on scientific articles and publications related to CNTs in construction were used to ensure the article's reliability, validity, completeness, and objectivity. The research highlights CNTs' potential as material enhancers in construction, owing to their unique mechanical properties, such as high strength, stiffness, and corrosion resistance. Specific studies demonstrating the use of CNTs to increase the strength of concrete and other construction materials are provided, indicating the promising application of CNTs in future construction projects. However, technical challenges must be addressed, and appropriate standards and regulations should be developed before practical implementation.

1. Introduction

The global construction industry is undergoing a paradigm shift as sustainability takes center stage in the pursuit of a greener and more environmentally conscious future [1]. Traditional construction materials like concrete and steel have long been essential for infrastructure development but contribute to environmental issues due to their carbon emissions and resource depletion [2,3]. To address sustainability concerns, carbon nanotubes (CNTs) have emerged as a groundbreaking alternative [4]. CNTs are microscopic cylindrical structures composed of carbon atoms, offering extraordinary mechanical, electrical, and thermal properties [5]. They are exceptionally strong yet lightweight, allowing for efficient load distribution and enhanced durability [6]. Integrating CNTs in construction materials provides several advantages. Their use significantly reduces the carbon footprint, as they enhance structural integrity and require less material, lowering energy consumption and greenhouse gas emissions during production and transportation [7,8]. CNTs also enable the development of self-sensing and self-healing materials, allowing real-time monitoring of structural health and microcrack repair, extending material lifespan, and reducing maintenance needs [9].

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Furthermore, CNTs offer opportunities for energy-efficient infrastructure through enhanced electrical conductivity for energy storage systems and smart grid technologies, and thermal conductivity for insulation materials, optimizing energy consumption in buildings [10,11].

While CNTs show immense promise, challenges like large-scale production, cost-effectiveness, and environmental risks must be addressed [12]. Continued research and collaboration between academia, industry, and policymakers are essential to unlock their full potential and pave the way for a sustainable future.

The unique properties of CNTs extend beyond construction, finding applications in various industries to improve material strength, deformability, and durability [13,14]. Their integration into construction materials creates new composites with enhanced characteristics, such as increased strength and reduced shrinkage in concrete. Functional coatings with properties like waterproofing, fire resistance, and corrosion protection can improve the quality and lifespan of construction materials [15,16]. The literature highlights the extensive research into CNTs in construction, showcasing their potential to revolutionize the field and create materials and structures with improved properties and efficiency. Nanotechnology, including CNTs, has opened exciting possibilities for the construction industry, enabling the development of innovative materials and structures [17,18]. Numerous review articles delve deeply into specific directions. For instance, Norizan et al. [19] provides a comprehensive review of existing research and introduces novel findings on the functionalization of carbon nanotubes to enhance their sensitivity and selectivity in detecting various chemical compounds. This advancement holds potential applications in diverse fields, including medicine, environment, and industry. The article highlights the significant role of carbon nanotubes as chemical sensors, emphasizing that functionalization can significantly enhance their performance and detection efficiency.

Garg et al. [20] explores the utilization of carbon nanotubes as strengthening agents in composite materials. The authors examine various methods for obtaining and evaluating carbon nanotubes, as well as their application in composite materials to enhance mechanical properties. The article discusses the potential advantages and limitations of integrating carbon nanotubes into composite materials.

Similarly, Anzar et al. [21] offers an overview of the diverse applications of carbon nanotubes in biomedicine. This encompasses their use as nanovectors for drug delivery, materials for tissue engineering, biomarkers, and various other applications. Fiyadh et al. [22] review different adsorption methods, investigate the mechanisms of interaction between carbon nanotubes and heavy metals, and provide an overview of parameters influencing adsorption efficiency, such as nanotube size, shape, pH of the medium and metal concentration. They further explore the application of carbon nanotubes in removing heavy metals from water solutions, soil, and wastewater.

Sajid et al. [23] present an overview of various applications of carbon nanotube-based adsorbents in water purification, including the removal of organic and inorganic pollutants, heavy metals, pharmaceuticals, and other harmful substances. The article discusses the interaction mechanisms between carbon nanotubes and water pollutants, encompassing adsorption and ion exchange processes.

The impact of carbon nanotubes on concrete properties is also examined in [24]. The review summarizes existing research on the use of carbon nanotubes in concrete and their influence on its mechanical and physicochemical properties. Various methods of incorporating carbon nanotubes into the concrete matrix, such as mixing, spraying, and modified nanotube application, are discussed, along with the effects on strength, elasticity, fracture resistance, and other mechanical properties of concrete.

Franklin et al. [25] primarily focuses on the assembly and modification techniques of carbon nanotube transistors, as well as the underlying principles of their electronic performance. The authors also address issues related to enhancing the efficiency and stability of carbon nanotube transistors. Additionally, the article presents examples of their applications in diverse fields, including electronics.

Alsubaie et al. [26] explores the vibration response of functionally graded carbon nanotube-reinforced composite (CNTRC) beams using a higher-order shear deformation beam theory. The beams are reinforced with single-walled carbon nanotubes in a polymer matrix and supported by a viscoelastic foundation. Various reinforcement distribution patterns and porosity distributions are considered. The study incorporates damping coefficient, Winkler's, and Pasternak's parameters to analyze viscosity effects on the foundation. Results indicate that adding a damping coefficient enhances vibration performance, especially with increased spring constant factors. The fundamental frequency rises with higher porosity coefficients, suggesting a significant impact of porosity on beam vibrational characteristics [26].

Madenci et al. [27] investigates the application of carbon nanotubes (CNTs) in strengthening polymer matrix composites through experimental tensile testing and fabrication of carbon nanotube reinforced composite (CNTRC) beams. The study explores various micromechanical models to optimize the mechanical properties of CNTRC materials. The research concludes that the optimal CNT amount for reinforcing composite beams is 0.3%, as higher concentrations lead to reduced tensile capacity. A comparison between experimental results and Finite Element Models using ABAQUS demonstrates good conformance. The study also evaluates Young's Moduli using the prediction models Halpin-Tsai and Mixture-Rule, revealing accurate predictions by Halpin-Tsai and significantly lower accuracy with Mixture-Rule [27].

Zhang et al. [28] investigates the wave propagation behavior of carbon nanotube reinforced composite (CNTRC) beams on an elastic foundation, employing various higher order shear deformation beam theories such as Euler and Timoshenko theories. Wave equations for CNTRC beams are derived using the Euler-Lagrange principle, and the relationship between wave number and circular frequency is established through the eigenvalue method. Phase and group velocities are determined as functions of wave number, and material properties of CNTRC beams are estimated using the mixture rule. Comparative analysis with Euler and Timoshenko beam theories is conducted to validate findings. The mathematical model is numerically verified against existing results, and the study explores the impact of CNT enhancement modes, volume fraction, spring factor, and other factors on CNTRC beam wave propagation behaviors [28].

Mangalasseri et al. [29] delves into the energy harvesting properties of a magneto-electro-elastic cantilever beam enhanced with carbon nanotubes (CNT) during transverse vibration. Employing a lumped parameter model to mathematically represent the coupled multiphysics problem, the study explores the impact of factors like CNT distribution, substrate material, and length-to-thickness ratio on energy harvesting behavior. The research aims to enhance comprehension of smart material-based energy harvesting systems, specifically those reinforced with CNT, offering potential implications for the design and analysis of CNT-based smart structures [29].

Arshid et al. [30] explores the vibration analysis of functionally graded microplates with polymeric nanocomposite patches, incorporating porosity and hygrothermal effects. The microplates feature three layers, including an FG porous core and piezoelectric nanocomposite face sheets with stiffness-enhancing CNTs. Using a quasi-3D shear deformation theory and modified couple stress theory, the equations of motion are derived. Figure-presented results allow assessment of material properties, geometry, foundation moduli, and hygrothermal effects on vibrational behavior. Findings indicate that increasing

CNT volume fraction improves mechanical properties, subsequently raising natural frequency. Notably, the study emphasizes the substantial impact of accounting for the hygrothermal environment in analyzing these structures [30].

Huang et al. [31] introduces a size-dependent model for analyzing the static stability of doubly curved micro-panels made of advanced composites reinforced with carbon-based materials. The research combines a seven-unknown shear deformation theory in curvilinear coordinates with a non-classical approach to assess the mechanical performance of micro-size shells accurately. Utilizing a virtual work of Hamilton statement and an analytical technique based on double-Fourier series, the study analyzes micro shells with fully simply supported conditions at edges. Results show that CNTs reinforced composite curved shells exhibit a hardening response under buckling, with the critical buckling load highest for spherical panels, followed by elliptical, cylindrical, and hyperbolic panels. Moreover, changes in CNTs weight fraction significantly impact the static stability characteristics of CNTs reinforced composite curved size-dependent shells [31].

Heidari et al. [32] addresses the need to enhance the realism of engineering models for nanocomposites, critiquing past studies that assumed idealized properties of carbon nanotubes (CNTs). The study focuses on incorporating real-world complexities like nanotube waviness, defects, and aggregation observed in experiments. It introduces size effects into nanocomposite models, validating their accuracy through comparisons with experimental data and theoretical models. The article presents numerical examples illustrating buckling behaviors of nanocomposites, emphasizing the application of nonlocal theory to account for size effects. Overall, it is the first comprehensive exploration of these aspects, providing a crucial reference for future research in nanocomposite materials [32].

Undertaking a comprehensive review in the field of carbon nanotube applications within building materials is justified by several compelling reasons. First, it offers a methodical framework for gathering and comparing data from a myriad of sources. This systematic approach enhances comprehension by researchers and engineers as they navigate the wealth of available information. Second, the review serves as a spotlight on the pivotal challenges confronted by those working with carbon nanotubes in building materials. Through this scrutiny, critical obstacles come to the fore, pinpointing areas ripe for further exploration and unveiling the realm's untapped potential.

Furthermore, this review becomes a tapestry that weaves together diverse data from research articles, patents, and technical reports. This comprehensive mosaic fosters a panoramic understanding while circumventing potential distortions from cherry-picked examples.

Despite the extensive research into carbon nanotubes, there are a number of gaps in this area. The first shortcoming is the lack of wider comparative research comparing the properties of many building materials with and without CNTs. This limits the ability to make an objective comparison and identify clear benefits of using CNTs in construction. Therefore, more detailed studies based on comparative analysis can be a valuable contribution to the field. In addition, a more detailed discussion of the technical issues and challenges associated with the industrial scaling up of CNT production and its economic feasibility is essential for the practical introduction of CNTs in the construction industry and requires further research and development. In light of the above, this study also aims to fill knowledge gaps and present new results related to the use of CNTs in construction. This review can also provide recommendations on how to overcome current technical and environmental challenges to ensure a more sustainable and efficient use of CNTs in the construction industry.

This review also covers all aspects of CNT properties and their impact on construction materials, allowing us to assess the full potential of CNTs and their applicability in various construction industries. Additionally, previous studies may be limited in their methodology and scope. Some may be based on a small sample of data or use outdated data analysis methods and tools. This paper improves the methodological approach using modern data analysis tools and a wide range of literature sources to obtain more comprehensive and reliable results.

The practical significance of this review article lies in its ability to systematically inform interested industries and to move towards a more sustainable future by exploring the potential use of CNTs as material amplifiers. The article highlights the problems that need to be solved before practical implementation and gives an idea of current research in this area.

2. Methodology

This section provides a comprehensive outline of the study's methodology. It begins with the careful formulation of research goals and objectives. A thorough search of scientific literature is conducted using Scopus and Google Scholar databases to gather a wide range of relevant works. The collected data undergo meticulous analysis using Python and VOSviewer software. Python is employed for data processing, statistical analyses, and result visualization, while VOSviewer aids in creating a visual representation of the literature landscape, highlighting key themes and authors. The study then delves into diverse methods for carbon nanotube production, including CVD, electrochemical deposition, and mechanical stretching, alongside insights from illustrative studies. Catalysts for CVD are scrutinized for their impact on nanotube formation. Strategies for integrating carbon nanotubes into building materials are explored, covering blending, coating, and functionalized nanotube incorporation, with a focus on enhanced properties. The research tasks encompass defining goals, selecting methods, investigating nanotube properties, and processing results. This culminates in drawing meaningful conclusions from the accumulated data and comparative analyses. The following steps outline the methodological process (Fig 1) :

2.1. Literature Search

A thorough literature search was conducted using two primary databases : the Scopus bibliographic and abstract database and the Google Scholar search engine. The search was performed by employing a combination of relevant keywords and phrases related to the research topic. The selected keywords were carefully chosen to ensure a comprehensive coverage of the relevant literature.

2.2. Data Extraction

After obtaining the search results, data from the Scopus database was downloaded in the RIS format (Research Information Systems) to facilitate further analysis. The RIS format is widely used for bibliographic data exchange and is compatible with various data analysis tools.

2.3. Data Analysis in Python

Data analysis was performed using the Python programming language, leveraging its powerful libraries for data manipulation and analysis. The bibliographic data downloaded in the RIS format was processed and cleaned to ensure the accuracy and consistency of the dataset. Python's data analysis libraries, such as Pandas and NumPy, were utilized for data cleaning, transformation, and preparation.

2.4. VOSviewer Analysis

In addition to the Python-based data analysis, the data was also imported into VOSviewer, a powerful bibliometric analysis software. VOSviewer allowed us to create visual representations of the co-occurrence of keywords, authors, and publications within the dataset. This analysis provided valuable insights into the most prominent research themes, patterns, and interconnections among different concepts.

2.5. Integration of Results

The findings from both the Python-based data analysis and the VOSviewer analysis were integrated to create a comprehensive picture of the literature landscape related to the research topic. The combined results enabled us to identify key research trends, influential authors, and significant clusters of related publications.

2.6. Interpretation and Discussion

The interpreted results from the data analysis were discussed in the context of the research objectives and existing literature. The implications of the findings were critically analyzed to draw meaningful conclusions and identify potential areas for future research.

By adopting this methodological approach, the study aimed to ensure a robust and systematic exploration of the existing literature and provide a solid foundation for the subsequent stages of analysis and discussion.

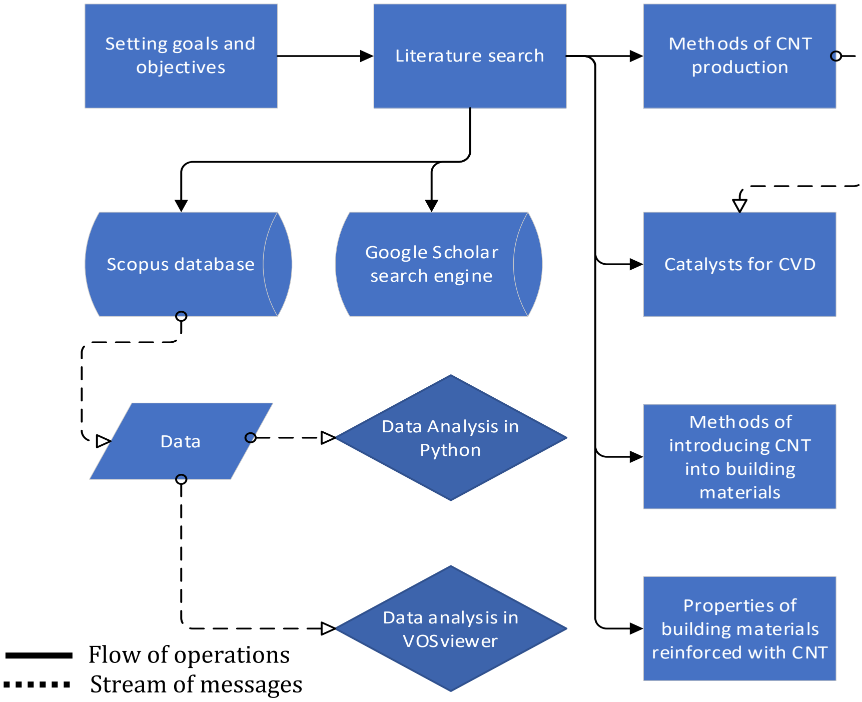

Fig. 1. Methodology flowcharte

3. Results and Discussion

3.1 CNTs Analysis in Research Literature: 2019-2023

To gather relevant information, a literature search was conducted using the Scopus bibliographic and abstract database, as well as the Google Scholar search engine. The search results were visualized using the VOSviewer software, which facilitated the analysis of keywords found in the publications. The data covered a significant number of articles for 2019-2023: a total of 57,633 articles were found. Of these, 11,816 articles for 2019 were used in visualization and analytics, 20,000 articles (due to the fact that Scopus database allows you to upload no more than 20,000 results to one file at a time) for 2020 (a total of 23,520 articles were found in 2020), 20,000 articles for 2021 year (23,580 articles were found), 20,000 articles for 2022 (24,490 articles were found) and 20,000 articles for 2023 (22,237 articles were found). This comprehensive study of research articles highlights the growing interest and importance of carbon nanotubes in various fields, including construction.

Figure 2 illustrates the distribution of frequently encountered keywords in publications over time. These keywords include nanocomposites, single-walled CNTs, polymers, supercapacitors, heat resistance, tensile strength, and other relevant terms. On the other hand, Figure 3 presents the clustering results of the same search query.

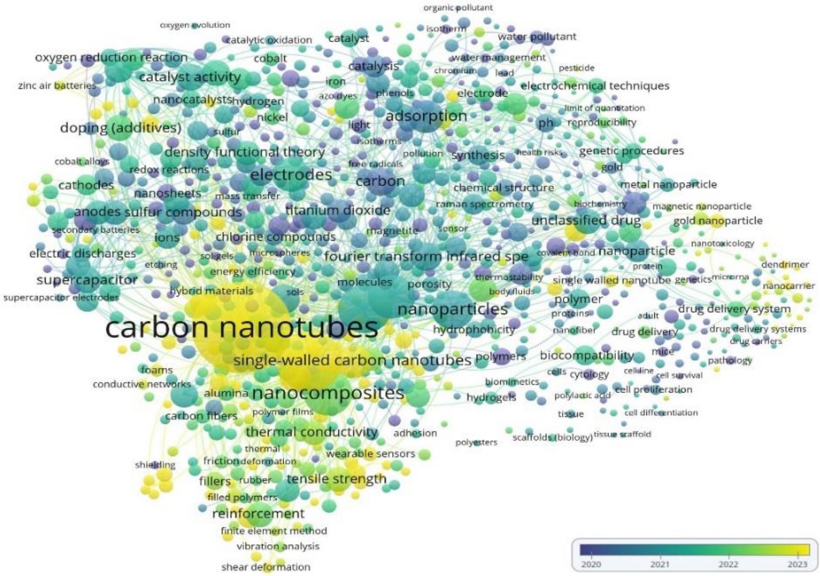

Fig. 2. Search results for "carbon nanotubes" in Scopus

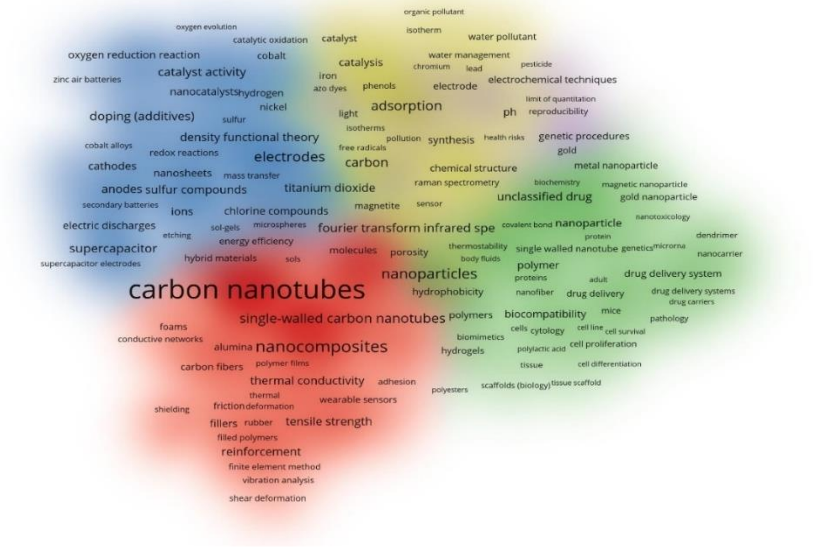

Fig. 3. Results of the "carbon nanotubes" search query in Scopus by cluster

A set of articles published between 2019 and 2023 related to the query "carbon nanotubes" was extracted. Subsequently, an analysis was conducted using Python scripts, and the Pandas and Matplotlib libraries were employed to process and visualize the data.

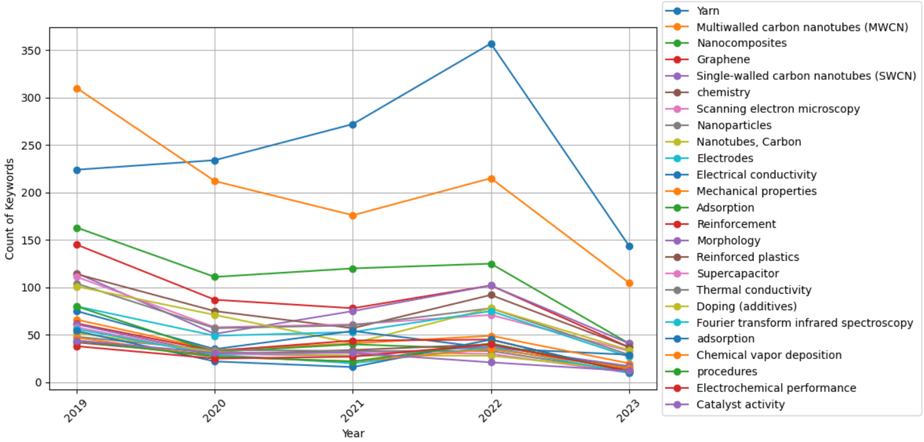

Fig. 4. Results of keyword analysis by articles

Figure 4 depicts the distribution of the 25 most frequent keywords in the articles, categorized by year (Fig 4). The results presented in Figure 4 were generated by excluding certain words from the search, namely "Review", "Article", "Priority journal", "Controlled study", "Graphene", "Carbon nanotubes", "Nanotechnology", and "Nanoparticle". These words were excluded due to their high frequency and tendency to appear in nearly all articles. Conversely, Figure 6 showcases a histogram containing all keywords, including the highly frequent ones, presenting the grouping of the 15 most frequent keywords by publication year.

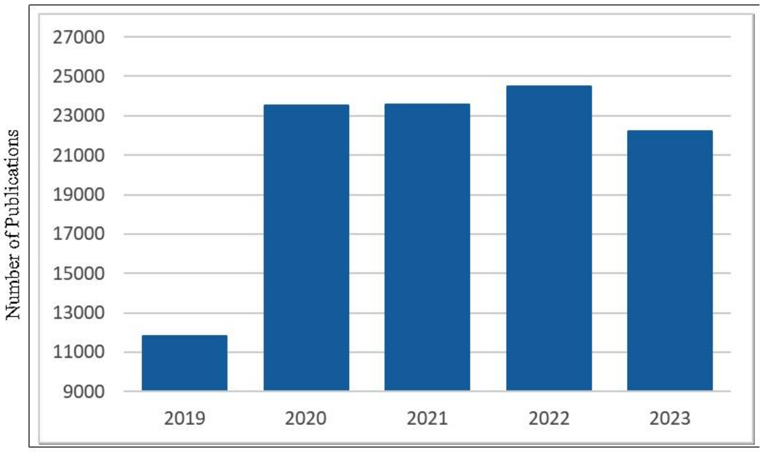

Fig. 5. Number of articles by year

Figure 5 shows a histogram of the total number of publications for the query "carbon nanotubes" in the Scopus database. As can be seen in Figure 5, the number of articles for this query peaks in 2022. The number of articles shows a decrease in 2023. This decrease in 2023 can be explained by the fact that the data only cover the period up to September 2023, which is not the full year of data collection.

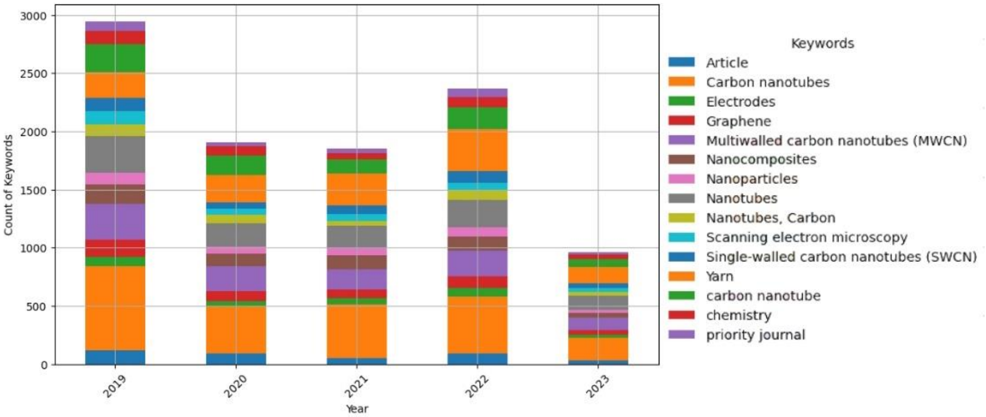

Fig. 6. The most high-frequency keywords

Using the Jupyter Notebook web development tool and the Word Cloud library, word clouds were generated to visualize the search results. The word cloud of frequently encountered words in the abstracts of review articles is displayed in Figure 7a, while Figure 7b presents the word cloud of high-frequency keywords. A cloud of words frequently found in the abstracts of all reviewed articles is shown in Figure 8a, and a cloud of high-frequency keywords is shown in Figure 8b. These visual representations offer an intuitive means to observe the prominence and relevance of various words within the search results.

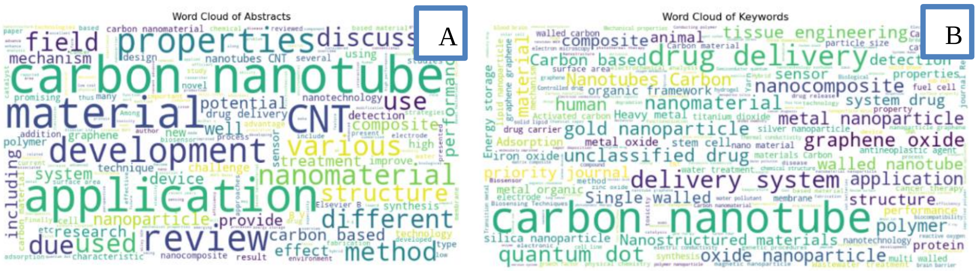

Fig. 7. Word cloud (a) abstracts of review articles, (b) keywords

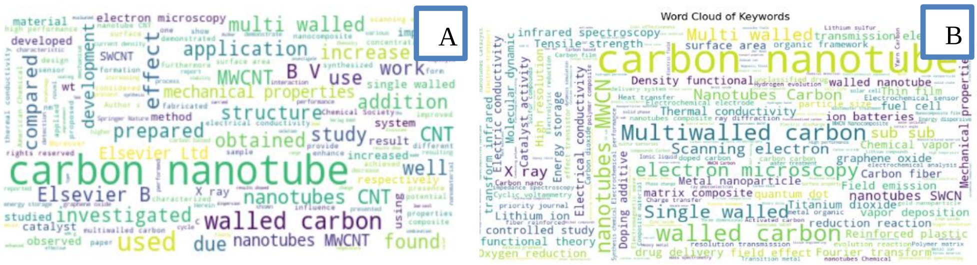

Fig. 7. Word cloud (a) abstracts of all articles, (b) keywords

3.2 Methods of CNT production

CNT production methods encompass various techniques used to create carbon-based nanotubes. Among them, the most common methods include hydrocarbon pyrolysis, laser ablation of graphite, electric arc synthesis, and chemical vapor deposition (CVD).

Hydrocarbon pyrolysis involves decomposing hydrocarbons into carbon and other byproducts to produce CNTs [33, 34]. This method is extensively utilized for large-scale CNT production. Pyrolysis of hydrocarbons, also known as pyrogenic synthesis, entails the decomposition of organic compounds into carbon, hydrogen, and oxygen at high temperatures. It is a widely employed approach for producing carbon nanomaterials like carbon nanotubes, fullerenes, and graphene.

Special equipment called a pyrolysis unit (Fig.8) is employed for the pyrolytic synthesis of hydrocarbons. The unit consists of a reaction chamber where the synthesis occurs and a gas supply system. To prevent contamination of nanomaterials, the reaction chamber is typically made of stainless steel or ceramics. The pyrolytic synthesis process initiates by heating the hydrocarbons to temperatures exceeding 700°C. At this temperature, the hydrocarbons decompose into carbon, hydrogen, and various gases. The carbon remains in the form of nanoparticles that subsequently aggregate.

One notable advantage of pyrolytic synthesis is its capability to produce carbon nanomaterials with high purity and uniformity. Furthermore, this method allows for control over the size and shape of the resulting nanomaterials. However, pyrolytic synthesis does have some drawbacks, such as high equipment costs and energy consumption. Additionally, the hydrocarbon pyrolysis method may not be suitable for producing all types of CNTs and may be limited in cases where specific properties are desired (e.g. high electrical conductivity or resistance to oxidation).

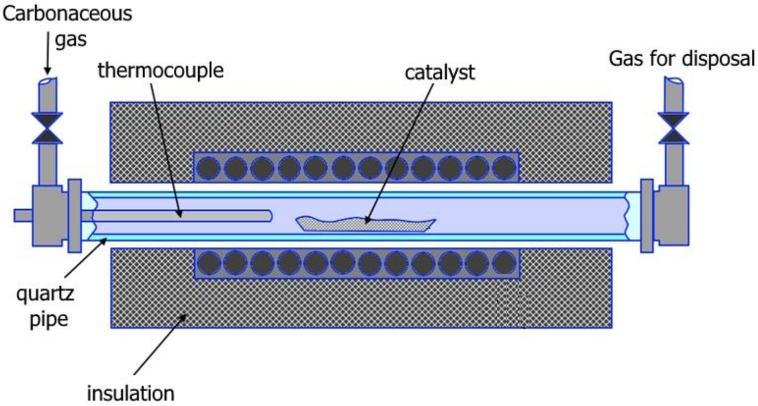

Fig. 8. Schematic diagram of a horizontal batch rector for pyrolysis of carbon-bearing gases [35]

Laser ablation of graphite involves the use of powerful laser radiation to evaporate and subsequently condense graphite in a vacuum (Figure 9). This process breaks down graphite crystals into individual carbon atoms, which then assemble into nanoparticles [36, 37].

Laser ablation of graphite is capable of producing ultra-dispersed carbon nanostructures, including carbon nanotubes, carbon nanofibers, carbon nanoribbons, and more. These nanomaterials possess unique properties such as high electrical conductivity and mechanical strength, making them highly promising for diverse applications. Additionally, laser ablation of graphite is an environmentally friendly method as it does not require the use of chemicals or high temperatures, thus making it attractive for industries like automotive, aviation, and space.

However, one of the main challenges associated with laser ablation is the difficulty in controlling the process of obtaining carbon nanostructures. The high temperature and pressure generated during ablation make it challenging to precisely control the size and shape of the resulting nanoparticles. This variability can impact the properties and application of the nanotubes. Another drawback is the high cost of laser ablation equipment and materials. This method necessitates expensive laser equipment and specialized materials like graphite. Moreover, the ablation process itself is time-consuming and energy-intensive. Low productivity can also be considered a disadvantage of laser ablation. While this method produces carbon nanostructures with a high degree of purity and uniformity, it may be less efficient compared to other nanoparticle production methods.

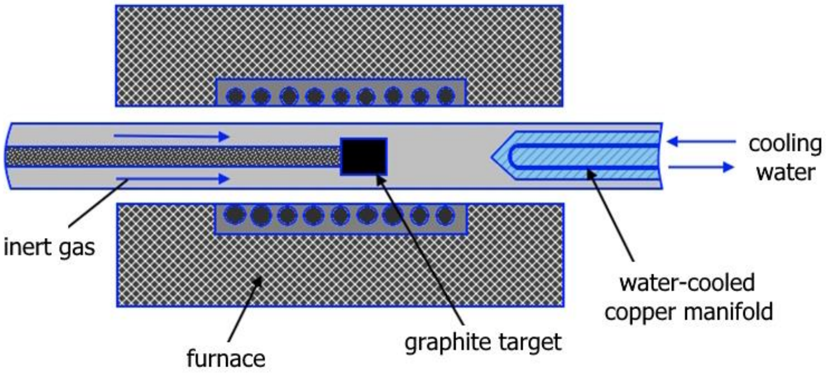

Fig. 9. Schematic diagram of a machine for CNT production by laser ablation [35]

In a study conducted by the authors [38], they successfully synthesized graphene sheets in two stages at room temperature and normal pressure. The process involved laser ablation of graphite, followed by repeated irradiation of suspensions after removing the graphite target. X-ray analysis confirmed the production of different carbon materials.

Several factors influence the synthesis of carbon nanotubes through laser ablation, including temperature, catalyst selection, choice of inert gas, laser power, wavelength, pressure, and fluid dynamics near the carbon target [39]. These parameters must be carefully controlled during the synthesis of CNTs.

Electric arc synthesis is another method utilized for producing CNTs. This technique involves the use of an electric arc to heat and melt a metal catalyst such as graphite or nickel (Fig.10). The molten metal is then cooled and crystallized, resulting in the formation of nanotubes. During the synthesis process, the nanotubes emerge from the catalyst and are collected in bundles, which can be subsequently cleaned and shaped to the desired size and form. The main advantages of electric arc synthesis for CNTs are its simplicity, speed, and controllability. Additionally, this method does not require the use of expensive catalysts, thereby reducing production costs.

Electric arc synthesis offers a versatile approach for producing various carbon nanomaterials, including carbon nanotubes and carbon nanoparticles, with diverse sizes and shapes. Despite its drawbacks such as high energy consumption and low yield, it remains a widely employed method in scientific and industrial fields involved in the synthesis and application of carbon nanomaterials [40, 41].

Chemical vapor deposition (CVD) is one of the most prevalent methods for producing carbon nanotubes [43, 43]. It enables the synthesis of large-diameter and high-purity CNTs. CVD involves the decomposition and condensation of organic compounds in the gas phase onto a catalyst surface at high temperatures.

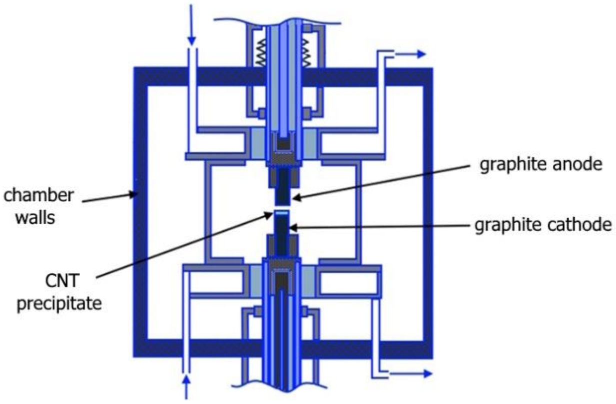

Fig. 10Schematic diagram of a plant for producing CNT by electric arc synthesis [35]

In CVD, specialized reactors are employed where high temperatures (typically ranging from 700 to 1,000 degrees Celsius) and pressures are maintained (Figure 11). The reactor is filled with a gas mixture comprising a reagent (e.g., benzene or acetylene) and a catalyst (commonly graphite or nickel). At elevated temperatures, the reagent decomposes into gaseous products, which subsequently condense on the catalyst's surface. This process leads to the formation of nanotubes that accumulate on the surface and continue to grow until they reach a specific diameter.

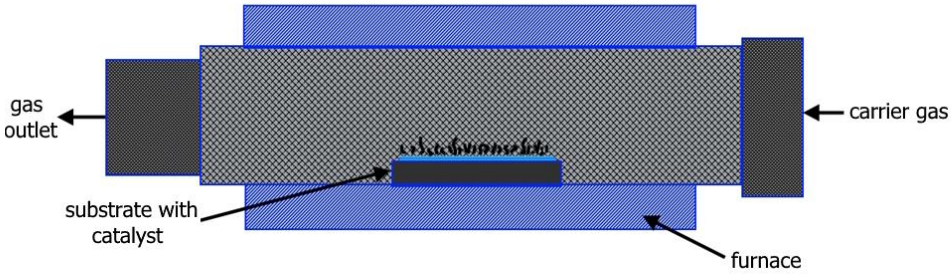

Fig. 11 Chemical vapor deposition (CVD) method [44]

Chemical vapor deposition (CVD) is not only utilized for producing carbon nanotubes but also for other types of carbon nanomaterials, including amorphous carbon and carbon nanoparticles. The method offers the advantage of controlling the size and shape of the resulting structures by adjusting process parameters such as temperature, pressure, and gas mixture composition. CVD is capable of generating nanotubes with varying diameters and shapes, making it a versatile technique for numerous applications.

CVD finds applications in various fields, including microelectronics. In microelectronics, CVD is employed for producing integrated circuits and other electronic devices. The method of CVD offers several advantages:

Precise control: CVD allows for meticulous control over the size and shape of nanomaterials through precise adjustment of process parameters.

High purity: CVD produces nanomaterials with high purity and low impurity concentrations due to its robust process control.

Convenience and efficiency: The CVD process are easily automated, enabling precise adjustment of process parameters. Moreover, the method is highly efficient, yielding significant volumes of nanomaterials.

Unique properties: CVD-derived nanomaterials often exhibit distinctive physical and chemical properties that are not typically observed in materials produced through other methods.

Thus, chemical vapor deposition is a powerful and effective approach for producing carbon nanomaterials with exceptional properties, making it a popular choice in scientific research [45, 46]. For instance, a study [47] compared single-walled carbon nanotubes produced via CVD with those obtained using an improved electric arc synthesis method. The results revealed that CVD-produced nanotubes exhibited superior dispersion into thin fibers, even at the monolayer level.

In another work [48], mechanical properties and corrosion resistance of composites reinforced with CVD-produced carbon nanotubes at varying mass fractions (0.1%, 0.2%, and 0.5%) were investigated. The study determined that the most corrosion-resistant structure was achieved in composites reinforced with 0.2% CNTs.

Chemical Mechanical Exfoliation (CME) is a method for producing high-purity carbon nanotubes (CNTs) through a combination of chemical and mechanical processes. The process involves the preparation of graphite as a starting material, followed by chemical functionalization to facilitate subsequent processing. Mechanical exfoliation, which can be achieved through various methods, separates graphite layers and forms CNTs. Purification and characterization complete the process, providing high-quality CNTs with controlled properties [49–52].

The Floating Catalyst Method utilizes catalyst nanoparticles suspended in a gaseous carbon source to produce high-quality CNTs. The process involves catalyst preparation, reactor installation, catalyst suspension in a carrier gas, introducing the carbon source, catalytic growth, nanotube recovery, and post-treatment. This method offers controlled CNT production with various properties but requires careful control of catalyst parameters and addressing potential impurities [53–55].

The Template-Assisted Growth method directs CNT growth using templates with defined nanopores. Steps include template preparation, catalyst deposition, introducing a carbon source, nanotube growth within the template's nanopores, template removal, and post-treatment [56–59]. This method provides precise control over CNT diameter, length, and alignment and is compatible with various substrates [60].

Plasma Enhanced Chemical Vapour Deposition (PECVD) is a technique for creating Uniform Nanotube Arrays (UNAs) via plasma-assisted chemical reactions [61–65]. It involves substrate preparation, precursor gas introduction, plasma discharge, thin film deposition, and post-processing. PECVD offers controlled UNA production, uniform characteristics, and versatility across different substrates for applications in various industries [66–68].

Electrochemical Deposition (ECD) is another method for producing UNAs on a conductive substrate through an electrochemical cell [69–71]. It involves substrate preparation, immersion in an electrolyte solution, application of an electric potential, nanotube growth, and post-processing [72–74]. ECD allows precise control over nanotube dimensions and produces uniform arrays for applications in energy storage, catalysis, sensors, and electronics [75–79].

Solvothermal Method: This method involves a hydrothermal reaction in a solvent at high temperatures and pressures to synthesize CNTs with controlled properties and structures [80–84]. The process includes precursor preparation, reactor setup, sealing, reaction and growth, cooling, product recovery, and post-treatment [85–88]. It shows promise for CNT synthesis but has limitations such as cost, complexity, and environmental impact [89–96].

Mechano-thermal Synthesis: This approach combines mechanical activation and thermal treatment to produce highly ordered and crystalline CNTs [97–99]. Mechanical forces are used to break down precursor carbon materials, creating amorphous carbonaceous precursors [100–102]. Subsequent thermal treatment at high temperatures transforms these precursors into well-aligned CNTs [103,104]. Challenges include the need for precise control of mechanical activation and high-temperature processing [105,106].

Flame Synthesis: This technique uses a controlled combustion process to generate CNTs by decomposing precursor solutions in a high-temperature flame [97,106,107]. It offers continuous and scalable production, allowing adjustments in CNT size, diameter, and structure. Challenges include controlling CNT growth and dealing with unwanted byproducts [106,108,109].

Chemical Vapor Infiltration (CVI): CVI involves the deposition of carbon atoms onto a substrate through the controlled decomposition of gaseous precursors [110–112]. It allows for versatile, large-scale production, and the ability to tailor CNT properties. Deposition conditions impact growth rate, structural characteristics, and alignment [113–116].

Electrolysis: The Electrolysis method applies an electric current to a carbonaceous electrode immersed in an electrolyte solution [117,118]. This process leads to the direct synthesis of CNTs, providing control over their growth conditions and properties[119,120]. Challenges include low yield, slow growth rates, and the need to control CNT morphology and purity [121–123].

Understanding the advantages and disadvantages of various CNT production methods is crucial for selecting the most suitable approach for specific tasks. Table 1 provides an overview of CNT production methods, offering brief descriptions of their principles of action along with their advantages and disadvantages. The benefits and disadvantages mentioned in this table are not exhaustive and may vary depending on specific process parameters and conditions.

Table 1. Methods of CNT production

The method	Principle of operation	Benefits	Disadvantages
Pyrolysis of hydrocarbons [124–132]	Decomposition of organic compounds at high temperature	Low cost, high performance, scalability, good controllability of process parameters	CNTs may contain impurities, which can reduce their quality and properties; small diameter of CNTs; CNTs may be less resistant to oxidation than nanotubes produced by other methods
Laser ablation of graphite [106,133–138]	Effects of laser radiation on carbon materials	Possibility to produce single- and multi-layer CNTs of different shapes, high purity	High equipment costs, limited product volume, difficulty in controlling process parameters
Electric arc fusion [139–145]	Heating of carbon materials in an electric arc	Production of various sizes of CNTs, high synthesis rate	Limited size, need for inert gases, high cost, risk of CNT damage
Chemical vapor deposition (CVD) [146–154]	Reaction between a carbon source and other reagents in the gas phase	Ability to produce CNTs on different substrates, control of size and shape of nanostructures, high productivity, scalability	Risk of reaction byproducts that can adversely affect the quality of the resulting tubes, difficulty in setting up the process

The method	Principle of operation	Benefits	Disadvantages
Chemical Mechanical Exfoliation (CME) [155–160]	Mechanical exfoliation of layered carbon materials	Simple and low-cost method, production of high-quality CNTs with good crystallinity	Limited scalability, difficulty in achieving uniformity in CNT properties
Floating Catalyst Method [55,161–168]	Suspension of catalyst nanoparticles in a gaseous carbon source	Production of single- and multi-walled CNTs, high purity, control over diameter and alignment	High equipment costs, limited product volume, difficulty in controlling process parameters
Template-Assisted Growth [58,59,169–175]	Utilization of templates or nanopores to direct CNT growth	Precise control over diameter, length, and alignment of CNTs, scalability	Template removal can be challenging, limited choice of template materials
Plasma Enhanced Chemical Vapor Deposition (PECVD) [63,65,176–179]	Chemical reaction in a plasma environment	High deposition rate, good control over CNT properties, compatibility with various substrates	Plasma-induced damage to CNTs, requirement for specialized equipment
Electrochemical Deposition [180–185]	Electrochemical reaction for CNT growth on a conductive substrate	Controlled growth of CNTs, precise control over dimensions and alignment	Limited scalability, potential for electrode contamination
Solvothermal Method [84,186–192]	Hydrothermal reaction in a solvent at high temperatures and pressures	Synthesis of CNTs with regulated properties and structures	Limited scalability, high temperature and pressure requirements
Mechano-thermal Synthesis [97,193–198]	Combination of mechanical activation and thermal treatment	Production of highly ordered and crystalline CNTs, scalability	Potential for impurities, careful control of mechanical activation parameters required
Flame Synthesis [199–205]	Controlled combustion of hydrocarbon or carbon-containing precursors	Continuous production, control over CNT size and structure, in situ functionalization	Challenges in controlling CNT growth and uniformity, potential formation of unwanted byproducts

The characteristics of nanotubes obtained can vary based on the method used and process conditions. In conclusion, each of these methods possesses its own advantages and disadvantages, and the selection of a specific method depends on the particular requirements and production conditions.

For instance, pyrolysis of hydrocarbons is the most commonly employed method; however, it may result in the formation of impurities and structural defects in the nanotubes. Laser ablation of graphite yields nanotubes with high purity but necessitates costly equipment. Electric arc synthesis produces nanotubes with larger diameters but incurs high energy costs. Chemical vapor deposition allows for precise control over the structure and properties of nanotubes.

Therefore, the choice of CNT production method should be justified and based on a compromise between quality requirements and economic efficiency.

3.3. Catalysts for CVD

Chemical vapor deposition (CVD) is a widely employed and cost-effective technique for manufacturing carbon nanotubes (CNTs). During CVD, CNTs are synthesized by depositing the dissociation products of hydrocarbons onto a metal catalyst that serves as a "seed," followed by the growth of nanotubes on the catalyst surface.

The selection of a suitable catalyst plays a crucial role in achieving efficient CNT generation through the CVD method. An ideal catalyst should possess a high surface area, acting as the active center for chemical reactions, and offer a sufficiently high temperature for carbide decomposition. These catalysts can also be employed in the synthesis of other carbon nanostructures like graphene or fullerenes. The choice of catalyst depends on the desired structure and properties of the nanoparticles.

Chemical vapor deposition catalysts are primarily composed of metals or their oxides and are instrumental in expediting the formation of carbon nanostructures. Nickel is one of the most commonly used catalysts for CVD, enabling the synthesis of CNTs with high purity and uniform structure. Other metals such as copper, chromium, and molybdenum are also utilized as catalysts. Additionally, carbon precursors like graphite or CNTs can function as catalysts for CNT synthesis.

For instance, a copper-based catalyst can be employed in CNT synthesis. When a carbon-containing gas such as acetylene is heated, nanotubes form on the copper surface, which can then be separated from the catalyst for various applications.

Numerous catalysts are employed for CNT production via CVD under diverse conditions. These catalysts include metals like iron (Fe), nickel (Ni), cobalt (Co), their alloys, as well as surface-modified metals and their oxides.

While iron and nickel were initially the most prevalent catalysts for CNT production through CVD, researchers have been exploring more effective catalysts in recent years to achieve high-quality CNTs [206–208]. Studies indicate that iron alloys with other metals such as copper (CuFe) or cobalt (FeCo) can enhance productivity and purity during the CVD process. In CVD, carbon nanomaterials are formed by the interaction between carbon and various gases, typically hydrogen, carbon monoxide, or acetylene. Catalysts can comprise metals, oxides, hydroxides, or other substances, accelerating the decomposition of carbon-containing gases into carbon atoms and molecules, which subsequently combine into nanostructures.

The choice of catalyst depends on the desired properties of the resulting nanomaterials and the specific synthesis conditions. Ongoing advancements in catalyst research for CNT production via chemical vapor deposition allow for continual updates and improvements to this method [209–218]. It is important to select the most appropriate catalyst for specific process conditions and the desired properties of the nanotubes.

Table 2 below presents catalysts and their properties for CVD. However, it is worth noting that the size and quality of CNTs may slightly vary depending on process conditions such as temperature, pressure, and gas mixture composition. The first column of Table 2 denotes the catalyst (or elemental basis for combined catalysts) with corresponding references to studies utilizing them for CNT production. The subsequent columns in Table 2 provides general information and characteristics of each catalyst, independent of the referenced studies in the first column. This is because catalyst properties can differ based on the process conditions of vapor deposition, including temperature and pressure. Therefore, selecting the most suitable catalyst for specific process conditions and desired nanotube properties is crucial.

Table 2. CVD catalysts

Catalyst	Diameter of nanotubes	Quality of nanotubes	Features
Ferrocene [219-221]	~ 10-20 nm	Low	Ferrocene-based nanotubes are not only of low quality, but also heterogeneous in width. | It is quite unstable and can form a heterogeneous film.
Ni [222-224]	~ 10-100 nm	High	Ni-based nanotubes are of high quality and have a single-wall structure. Quite cheap and widespread catalyst. Provides high quality nanotubes and very few defects in the structure.
Co [225,226]	~ 5-50 nm	Very high	Co-derived nanotubes are of very high quality and have a single-wall structure, which makes them possible for use in electronics. It is also a cheap catalyst.
Fe [227-230]	~ 10-100 nm	Average	Fe-based nanotubes are of average quality and may contain additional defects in the structure. It is chemically stable but forms a lower quality film than Ni, Co.
Al [231,232]	~ 10-60 nm	Average	Al-based nanotubes are of average quality and may contain additional defects in the structure. It is not the best catalyst, but can be used to produce nanotubes of a certain type.
Pt [233,234]	~5-50 nm	Very high	One of the best sparse catalysts: provides very high quality and purity of nanotubes.
Pd [235,236]	~5-50 nm	Very high	Similar to Pt in its characteristics, but cheaper.
Ti [237]	~5-100 nm	Average	Provides good quality nanotubes and a structure different from that obtained with other catalysts.
Mo [238]	~5-50 nm	Average	It can be used to produce multiwalled nanotubes.
Cu [239-242]	~5-50 nm	High	It has high catalytic activity for CVD reaction. It can be used to produce nanotubes of different materials.
Au [243,244]	~5-50 nm	Low	It is not the best catalyst for the CVD reaction and is not normally used for producing nanotubes.
Co Ni Au [235]	Various sizes	Miscellaneous	Combinations of catalysts can combine the advantages of different materials. For example, the combination of Co and Ni gives very good nanotube quality, and the combination of Ni and Au gives good charge transfer properties.

Table 2 clearly illustrates the substantial variation in cost, nanotube quality, and defectiveness among catalysts. The selection of a specific catalyst depends on numerous factors, including availability and cost. For instance, Fe serves as an inexpensive catalyst, enabling the production of nanotubes at low temperatures and pressures. However, the resulting nanotubes exhibit lower quality and often contain numerous defects. On the other hand, Pt is highly expensive but yields high-quality nanotubes with a low defect rate. Moreover, catalysts can be combined to enhance results [246-249]. For example, the combination of Ni and Co yields nanotubes of the highest quality and low defect levels, whereas the combination of Cu and Ni enables the production of nanotubes with diverse materials.

This section provides a concise overview of catalysts utilized in the CVD method, underscoring their significant influence on the properties of carbon nanotubes. Consequently, selecting an appropriate catalyst becomes crucial in achieving desired carbon nanotube properties, such as size and structure, and should align with specific requirements.

3.4. Methods of Introducing CNT Into Building Materials

The incorporation of carbon nanotubes (CNTs) into building materials has emerged as a novel and increasingly popular strategy for enhancing their mechanical and physical properties. Recent years have witnessed numerous studies exploring the utilization of CNTs in diverse building materials, including concrete and reinforced polymers [250,251].

Mechanical introduction stands out as one of the primary approaches for integrating CNTs into building materials. This method involves simply adding nanotubes to the material during its preparation in the form of dust, powder, or liquid. To ensure a more uniform dispersion of CNTs within the material, techniques such as ultrasonic or magnetic treatment can be employed [252–254]. Ultrasonic processing facilitates the pulverization of CNT particles, leading to their more even distribution throughout the material. Similarly, magnetic treatment can be utilized to fractionate CNT particles into smaller sizes, thereby enhancing their dispersion within the material [255,256].

In addition to mechanical introduction, other processing techniques can be employed to enhance the efficacy and quality of the CNT incorporation process. Surfactant functionalization is one such method, where surfactants are used to improve the wettability of CNTs, allowing for better dispersion within the matrix [257–261]. Sonication, which utilizes high-frequency sound waves, can also be used to break up CNT agglomerates and ensure better dispersion [262–265].

The specific method of incorporating CNTs into building materials depends on the desired properties and operating conditions. For example, in the case of concrete, CNTs can be added as nano powders or through the creation of functional coatings [266–268]. This helps improve the strength, corrosion resistance, and shrinkage reduction of the concrete. For materials like bricks and glass, functional coatings and nano powder addition can enhance properties such as fire resistance, thermal insulation, transparency, and scratch resistance [269,270].

In the case of metals, including steel and aluminum, CNTs can be introduced through the addition of nano powders or by creating functional coatings [271,272]. This improves the durability and corrosion resistance of the metals [273–275]. Plastic materials can also benefit from the addition of CNTs in the form of a liquid additive, which enhances wear resistance and durability [276,277]. Similarly, the addition of CNT powder to rubber materials improves wear resistance and elasticity [278–280].

These examples highlight the versatility of CNT incorporation, as different materials can be enhanced by utilizing CNTs in various ways. The selection of materials and the specific method of introducing CNTs depend on the desired improvements and the specific requirements of each application. Continued research and collaboration among material scientists, engineers, and industry professionals will drive further advancements in this field, opening up new possibilities for the construction industry.

In essence, the mechanical introduction of CNTs represents one of the most commonly employed methods for their incorporation into building materials, with additional processing techniques employed to enhance the efficacy and quality of the process. Table 3 provides a concise overview of exemplary building materials exhibiting improved properties, along with the prevalent methods employed for incorporating CNTs into their structural composition.

Table 3. Construction materials with improved CNT properties

Construction materials	Improved properties	Methods of introducing CNT into building materials
Concrete [281–286]	Strength, corrosion resistance, shrinkage reduction	Adding nanopowders, creating functional coatings
Brick [287–291]	Resistance to fire, improved thermal insulation	Creating functional coatings, adding nanopowders
Glass [292–296]	Transparency, scratch resistance	Adding nanopowders, creating functional coatings
Metal [297–302]	Durability, corrosion resistance	Adding nanopowders, creating functional coatings
Plastic [303–307]	Resistance to wear and tear, durability	CNT liquid additive
Rubber [308–315]	Wear resistance, elasticity	Addition of CNT powder

These examples provide a glimpse into the diverse range of materials that can be enhanced by incorporating Carbon Nanotubes (CNTs). The selection of materials and the method of introducing CNTs depend on specific requirements and operating conditions governing each case.

CNTs offer tremendous potential in strengthening building materials by augmenting their mechanical properties, including increased strength, stiffness, impact resistance, and abrasion resistance. Furthermore, CNTs can impart electrical or thermal properties to materials, thereby expanding their functionality. However, the practical utilization of CNTs beyond the confines of laboratory settings is still constrained. One of the primary challenges involves achieving a uniform dispersion of CNTs within the material while preventing their aggregation, as such clustering can substantially compromise the material's quality [316–317].

Presently, nanotechnology finds active application across various industries. One significant application area involves the modification of building materials to enhance their properties. This section elucidates the methods employed for introducing CNTs into building materials and explores their potential application in creating efficient and secure building structures.

3.4.1. Mechanical Methods

One approach for incorporating carbon nanotubes (CNTs) into building materials is through mechanical methods. These methods rely on simple mechanical processes to introduce CNTs into the structure of the material. Ultrasonic dispersion is a technique where CNTs are dispersed within a material using ultrasonic waves. The waves create cyclic compression and tension zones in the material, resulting in the dispersion of nanoparticles. This method is highly efficient and produces nanometer-sized particles, enabling the production of materials with enhanced strength and durability. For instance, researchers [318] investigated the impact of multi-walled carbon nanotubes (MWNTs) with varying internal diameters on the mechanical properties and microstructure of cement-based materials. Ultrasonic dispersion was employed to uniformly distribute MWNTs within the cement-based materials. Experimental results demonstrated that increasing the diameter of MWNTs modified the flexural and compressive strength of cement-based materials.

Ultrasonic dispersion is a widely used method for incorporating carbon nanotubes (CNTs) into building materials. This process involves subjecting CNTs to high-frequency sound waves (typically in the range of 20-100 kHz) to break up agglomerates and disperse individual CNTs throughout the material matrix. The equipment used includes a sonicator, which generates the sound waves, and a vessel containing the material to be dispersed. The power output and frequency depend on the application and material properties [319,320].

Ultrasonic dispersion not only breaks up agglomerates but can also functionalize CNTs by introducing chemical groups onto their surfaces. This enhances their compatibility with the matrix and improves mechanical properties. The smaller size of dispersed CNTs (typically tens of nanometers) leads to a more homogeneous distribution within the matrix. One advantage of ultrasonic dispersion is its ability to achieve a more uniform dispersion of CNTs, enhancing the mechanical properties of the material. It also reduces agglomeration of CNTs, preventing the formation of large clusters that could negatively impact the material's properties. Furthermore, ultrasonic dispersion enhances the interfacial bonding between CNTs and the material matrix, improving load transfer and the overall integrity of the composite material.

Mechanical activation is another method where the material is mechanically loaded to activate the surface and create defects. These defects, including dislocations, voids, and microcracks, facilitate strong bonding between CNTs and the building material, resulting in a composite material with improved strength and durability [321,322]. Researchers [323] investigated various modified cement composites produced through mechanical activation. They utilized superplasticizers and CNTs with different structures and functionalities as modifiers. The study revealed that the bio resistance coefficient values of cement composite samples obtained by mechanically activating the binder and incorporating superplasticizers were 13% higher than those of the control composition.

Mechanical exposure involves saturating the material with CNTs using moving parts such as mills or mixers. This method generates high mechanical energy, breaking down the CNTs into nanometer-sized particles that then penetrate the material. By employing this approach, it is possible to produce materials with enhanced strength and durability while minimizing the quantity of CNTs required [324–326].

Overall, the utilization of mechanical methods for introducing CNTs into building materials enables the creation of materials with nanoparticle reinforcement, resulting in improved strength and durability. However, achieving the maximum effect requires careful selection of the optimal component ratios and material processing techniques.

3.4.2. Electrochemical Methods

Electrochemical techniques offer highly effective means of incorporating carbon nanotubes (CNTs) into various building materials, including concrete, asphalt, and polymer composites. One such technique is the electrochemical deposition of thin carbon films onto the material surface. This process involves depositing carbon nanoparticles onto the material surface by applying an electric current in a solution containing suitable reagents [327–329]. The method finds wide application in diverse fields, including electronics, catalysis, cosmetics, as well as scientific research in nanotechnology and materials science.

Electrochemical carbon deposition has proven beneficial in several areas. Firstly, it can be used to coat electrodes, thereby enhancing their conductivity in different devices and systems [330,331]. Secondly, carbon coatings serve as catalysts on material surfaces, improving the efficiency of processes such as electrolysis or gas synthesis. Additionally, carbon coatings find application in the production of electronic components like supercapacitors and solar cells.

The advantages of electrochemical carbon deposition include precise control over the deposition process, the ability to create thin, uniform, and high-quality carbon films, cost-effectiveness compared to other coating methods, and the potential to modify the properties of carbon coatings to suit specific needs [332–334]. However, there are also certain limitations associated with this technique. It requires careful adjustment of the deposition process to achieve the desired surface properties, and there may be defects in the film structure that could impact its properties. Furthermore, there are limitations on the types of materials onto which the coating can be applied.

Kim et al. demonstrated the use of a chemical deposition method to enhance the performance of a fuel cell electrode by employing CNTs and a Pt catalyst as the foundation. Their results indicated that the number of catalytic centers in Pt/CNTs obtained through electrochemical deposition was approximately three times higher [335]. Another study by Lee et al. proposed an efficient and practical approach for creating a new composite comprising ultrathin nanowire films by combining an assembly process with cost-effective electrochemical deposition technology [336].

Electrodeposition, another method for introducing CNTs into building materials, involves embedding CNTs into the material surface through an electrochemical reaction. The process utilizes an electric field to deposit CNTs onto the material surface. CNTs, serving as nanoparticles, enhance the properties of building materials that typically consist of metallic or polymeric components. The electrodeposition process begins with the preparation of a solution containing CNTs, which is then placed in an electrolytic bath. The material is immersed in the bath and connected to an electrode, while another electrode connected to an electric current source is positioned adjacent to the material. Subsequently, the electrodeposition process initiates, resulting in the deposition of CNTs onto the material surface.

This method offers advantages such as simplicity and the ability to control material conductivity by adjusting the CNT concentration in the solution. Additionally, materials obtained through CNT electrodeposition exhibit good shape and size matching, reducing the likelihood of defects [337,338]. However, this method has drawbacks, including a relatively low CNT concentration compared to other CNT introduction methods and the requirement for specialized equipment, making it a relatively complex process.

3.4.3. Chemical Methods

Chemical techniques offer a range of possibilities for incorporating Carbon Nanotubes (CNTs) into building materials, resulting in the development of materials with exceptional properties, including enhanced strength, thermal conductivity, and electrical conductivity. However, each method possesses its own set of advantages and disadvantages, and the selection of a specific technique depends on the intended purposes and requirements of the manufactured materials.

One such method is chemical deposition, which involves depositing a CNT solution onto the surface of the material [339–341]. This process begins by preparing a solution containing CNTs in a specialized liquid, typically ethylene glycol or other solvents. Various application techniques such as spraying or dripping are employed to apply the nanotube solution onto the material's surface.

Another method, known as metal fusion, employs the combination of different metals to coat the material's surface. This technique involves mixing CNTs with metal powders and subjecting them to high temperatures to form a composite material. Metal fusion exhibits notable advantages, including high wear resistance and excellent thermal conductivity, making it suitable for the production of construction materials like metal structures and pipelines.

The metal fusion method finds extensive use in modern industries, enabling the production of high-quality composite materials with unique properties unattainable by conventional carbon steels and other materials [342–345]. The process of metal alloying comprises several steps:

Alloy preparation: Various methods, such as mechanical mixing of metal powders with CNTs in a ball mill, are utilized to create a homogeneous mixture.

Material formation: The mixture from the previous step is heated to temperatures typically exceeding 1000 degrees Celsius, causing the metal powders and CNTs to merge and form a homogenous material with the desired properties. Heat treatment: Heat treatment is necessary to enhance the material's mechanical properties and harden it. The composite material is subjected to specific temperatures during heat treatment and subsequently cooled down. The advantages of the metal fusion method for building material production are numerous. These include high resistance to wear and mechanical damage, excellent thermal conductivity, significant resistance to corrosion and chemical reactions, and the ability to produce composite materials in various shapes and sizes.

In summary, chemical methods, such as chemical deposition and metal fusion, allow for the integration of CNTs into building materials, offering exceptional properties [346–349]. The choice of method depends on specific requirements, with metal fusion providing excellent wear resistance, thermal conductivity, corrosion resistance, and versatility in creating composite materials with unique shapes and sizes.

3.4.4. Physical Deposition Methods

Physical deposition methods for carbon nanotubes (CNTs) encompass a range of technologies and processes utilized to distribute nanotubes onto the surfaces of building materials.

Ion-beam deposition is a technological process that employs ion streams to generate thin coatings on material surfaces [350,351]. The process initiates by producing a high-frequency flux of ions dispersed in a gas medium, typically within a vacuum. The flux is then directed towards the substrate where the coating is intended to adhere. The ion flux is separated into positive and negative ions.

The distinctive feature of ion-beam deposition lies in the ability to precisely control the size, energy, and velocity of the ions. This enables the production of thin coatings with thicknesses ranging from fractions of a micron to several micrometers. When the ion flux impacts the material surface, it induces various chemical reactions and alterations in the CNT molecules, resulting in the formation of a thin layer on the material surface. These coatings can be created from a diverse range of materials, including ceramics, metals, plastics, and glass [352–355].

Ion-beam deposition finds extensive applications in the manufacturing of various devices such as microprocessors, sensors, optical devices, and more [356–358]. During the ion-beam deposition process, several factors need to be considered, including ion energy, the type of ions employed, the deposition medium, and the pressure within the vacuum chamber.

Magnetron sputtering is a technology employed to produce thin coatings on diverse material surfaces [359–362]. In this process, materials are atomized within a vacuum and then deposited onto the target surface. Special generators generate electric and magnetic fields within the working chamber to initiate the sputtering process. Atomized materials find applications in various industries, including electronics production, solar cells, medical products, and others. Magnetron sputtering enables the production of coatings with different characteristics based on specific requirements [363–365].

In a particular study [366], the authors discussed various applications of magnetron sputtering in the development of crucial materials for lithium batteries, categorized according to battery components such as electrode materials and solid electrolytes. The authors also proposed future prospects to drive the advancement of magnetron sputtering technology.

Vacuum cathode discharge represents one of the methods for growing CNTs on material surfaces [367,368]. It involves utilizing a vacuum chamber with a cathode composed of graphite or other carbon materials. When a high-frequency discharge passes through the chamber between the anode and cathode, CNTs begin to grow on the cathode's surface. The key advantage of this method is the ability to create CNTs with predetermined characteristics, including length, diameter, and structure. Additionally, this method is relatively straightforward and controllable.

However, there are also certain disadvantages. The CNT growth procedure within the vacuum chamber requires significant energy and time, which poses challenges for scaling up this method for industrial applications. Furthermore, the equipment cost for vacuum cathode discharge is relatively high. Nevertheless, vacuum cathode discharge remains an effective method for CNT creation in specific applications such as electronics, catalysis, and other fields [369,370].

3.4.5. Nanotechnology Methods

Electron beam lithography represents a cutting-edge technology used to fabricate micro- and nanostructures through controlled local treatment of a material's surface with an electron beam [371–374]. By employing this technology, carbon nanotubes (CNTs) can be incorporated into construction materials to enhance their mechanical properties. The process of introducing CNTs using electron beam lithography involves several key stages:

- Surface Preparation: The material's surface is meticulously cleaned and machined to create a specific pattern suitable for CNT integration.
- Applying Resist: A resist material, capable of undergoing changes when exposed to an electron beam, is applied onto the material's surface.
- Exposure: An electron beam is precisely directed onto the resist-coated surface, resulting in the formation of the desired pattern.
- Manifestation: The resist material that has been exposed to the electron beam is selectively removed from the areas corresponding to the pattern.
- Application of CNTs: A solution containing CNTs is applied onto the material's surface, specifically targeting the created pattern. This procedure reinforces the mechanical properties of the material at the required locations.
- Cleaning: Excess resist and any remaining residues are thoroughly eliminated from the material's surface.

This method of material reinforcement enables the production of lightweight yet robust and durable materials suitable for various construction applications [375,376]. Electron beam lithography serves as an effective approach to bolster building materials, facilitating the creation of more dependable and long-lasting structures [377–379].

Another technique involves incorporating CNTs into construction materials using a paramagnetic filler, which operates on the principles of electromagnetic induction [380–382]. Initially, CNTs are synthesized via chemical vapor deposition (CVD) using a suitable catalyst. Subsequently, the dispersion of CNTs in a solution containing a paramagnetic filler is performed to generate a nanocomposite. In some cases, the CNTs are treated with the paramagnetic filler before dispersion. The nanocomposite undergoes further treatment using an electromagnetic field created through electromagnetic induction. The paramagnetic filler within the solution responds to the induction field and adheres to the CNTs, resulting in the formation of an electromagnetic composite.

Consequently, a composite material comprising CNTs embedded with paramagnetic fillers is obtained [383–385]. This approach enhances the composite's magnetic susceptibility while simultaneously improving its mechanical and functional properties. The integration of CNTs using paramagnetic fillers presents a promising avenue for developing novel construction materials with enhanced characteristics. Although some of these methods can be expensive and require specialized equipment and expertise, they enable the creation of stronger and more flexible building materials utilizing the potential of CNTs.

Table 4. Methods of CNT introduction

Group	Methods	Principle of operation
Mechanical methods	Ultrasonic dispersion [386–388]	Mechanical impact creates pores in the material, where CNTs are then inserted
	Mechanical activation [307,389]	Mechanical impact creates pores and cracks in the material, where CNTs are then introduced
	Mechanical impact [390–393]	Mechanical impact creates additional spaces for nanotubes
Electrochemical methods	Electrochemical deposition [394–398]	An electrochemical process using a metallic cathode that serves as a current-carrying element
	Electrodeposition [399–403]	Using electrodeposition to create a thin layer of carbon inside the material
Chemical methods	Chemical deposition [404–407]	Using catalysts to create CNTs
	Metal alloying method [408–412]	A method that uses metal fusion to create organic compounds, which are then replaced by CNTs
Physical deposition methods	Ion Beam Deposition [378,413–416]	Using ion-beam deposition to create a thin layer of carbon on a material surface
	Magnetron sputtering [417–422]	Using magnetron sputtering of carbon to create a film on the material surface
	Vacuum cathode discharge [360,416]	Using vacuum cathodic discharge to create a thin layer of carbon on the material surface
Nanotechnology methods	Electron beam lithography [375,378,424,425]	Using a lithographic process to create microchannels on the material surface, where CNTs are then added
	Nanotubes with paramagnetic filler [385,426–429]	Using paramagnetic particles to trap CNTs in solution and direct them to the surface of the building material. The nanotubes then remain on the surface of the material and form a protective layer

Integrating carbon nanotubes (CNTs) into building materials offers numerous advantages, such as enhanced strength, increased resistance to corrosion and wear, and improved thermal insulation properties [340,430–433]. However, prior to their utilization in construction, extensive research and testing are imperative to ensure both their safety and effectiveness.

The study of CNT properties and their application in building materials is a rapidly advancing field in science and technology. Within this realm, the exploration of methods for incorporating CNTs into building materials holds considerable significance as a subject of investigation.

To summarize, the methods employed to introduce CNTs into building materials exhibit considerable potential for creating more robust and long-lasting materials. Nonetheless, it is essential to consider the specific characteristics of each method and assess its efficacy under distinct conditions. Furthermore, continuous research in this domain is vital to develop novel approaches and optimize existing ones, ultimately achieving optimal outcomes.

3.5. Properties of Building Materials Reinforced with CNT

In the past few years, there has been a growing interest among engineers and scientists in enhancing the quality of building materials to ensure better protection and durability for structures against external forces. One promising avenue of research involves the incorporation of carbon nanotubes (CNTs) to reinforce these materials [434–438]. In this section, we will explore the characteristics of building materials that are strengthened by CNTs. It is important to note that the concentration of CNTs and other relevant parameters can have a significant impact on the properties of these materials. Gaining a thorough understanding of these properties can be valuable for the development of novel materials that can construct more dependable and long-lasting buildings and structures. Nonetheless, it is crucial to consider the issues of economic feasibility and environmental safety when pursuing these advancements.

3.5.1. Mechanical Properties

The reliability and durability of construction materials heavily rely on their mechanical properties. A promising area of research in this field involves the utilization of Carbon Nanotubes (CNTs) to enhance the strength of materials.

Strength: Research studies indicate that the incorporation of CNTs into building materials can substantially enhance their strength. Factors such as the concentration of nanotubes, their position within the material matrix, and the size of the matrix particles have a significant influence on strengthening the material. Furthermore, nanotubes can mitigate thermal stresses caused by temperature fluctuations, which further contributes to the material's strength.

Shi et al.[439] outlines the principal characteristics of carbon nanotubes/nanofibres, the techniques for dispersing CNTs in cement-based materials, and the properties of CNT-based materials following modification with cement. The study affirm that the inclusion of CNT enhances the mechanical characteristics of cementitious materials.

The investigation of Jung et al. [440] employed diverse quantities of CNTs (0, 0.2, 0.5, 0.8, 1.0 and 2.0 weight percent). Prior research has indicated that introducing CNTs into cement-based materials can enhance their mechanical characteristics and cut down on porosity. Nevertheless, surpassing a certain concentration result in a decline in compressive strength.

Research conducted by Thomoglou et al. [441] suggests that the optimal amount of CNTs in cement mortar can provide improvements in various mechanical properties. Specifically, it was found that the incorporation of 0.2 wt% MWCNTs resulted in an increase in flexural strength by approximately 5.7%, compressive strength by 18.4%, 6.2%, and 8.8% for nano-, micro- and hybrid-modified cement mortars, respectively, compared to conventional mortars. These findings highlight the potential of CNTs in enhancing the mechanical performance of construction materials.

Stiffness: The introduction of CNTs can also increase the stiffness of building materials. Numerous experiments have demonstrated that as the concentration of nanotubes increases, the stiffness of the material also increases. Moreover, the deformation mechanisms induced by the presence of nanotubes can enhance the material's overall stiffness.

Kumar et al.[442] introduces the dynamic stiffness method (DSM) as a tool for analyzing the vibrations of multilayered plates containing carbon nanotubes (CNTs). The authors apply the Vitruvian-William method to solve the frequency-dependent stiffness matrix, allowing for an examination of the effects of various parameters on the plate and layer configuration. The findings from this study can be valuable for the design of multilayered FG-CNT structures, providing insights into optimizing their vibrational characteristics and performance.

Li et al. [443], the authors focus on the enhancement of compressive stiffness in graphene aerogels using a unique approach inspired by the structure of leaves. By incorporating carbon nanotubes (CNTs) into the aerogel matrix, they create a new material called CNT-interlayered graphene aerogels (CSGAs) through the process of freeze drying. The researchers conduct compression tests and observe that the presence of CNTs effectively reinforces the mechanical support of the aerogels, with the properties of CSGAs being influenced by the content of CNTs. Furthermore, molecular dynamics modeling reveals that an optimal concentration of CNTs forms a stable mesh structure, thereby preventing deformation of graphene nanosheets during bending. This study presents a promising strategy for the design of highly efficient graphene-based nanomaterials, thereby expanding the range of potential applications for these materials.

Fracture Resistance: CNTs can enhance the fracture resistance of building materials. For instance, studies have shown that carbon nanotubes can absorb impact energy and localize material damage [444–447]. This characteristic proves particularly valuable in safeguarding buildings and structures from the detrimental effects of explosions or natural disasters.

Table 5 presents a summary of the mechanical properties of CNT-enhanced materials in comparison to conventional building materials. The table encompasses four key characteristics of the materials: compressive strength, tensile strength, wear resistance, and corrosion resistance. According to the table, materials treated with CNTs exhibit significantly higher compressive strength, tensile strength, and wear resistance when compared to most industrial construction materials. However, it is important to note that the properties of improved CNT materials can vary considerably depending on the specific type of material and the technology employed.

Table 5. Characteristics of the properties of building materials with CNT

Characteristics	Most building materials	Materials improved by CNT
Compressive strength [448–452]	Relatively low	Up to 4 times higher
Tensile strength [453–458]	Relatively low	Up to 10 times higher
Resistance to wear and tear [459–465]	Relatively low	Up to 5 times higher
Corrosion resistance [466–475]	Relatively low	Above

Studies of the properties of building materials reinforced with CNTs show that this approach can significantly improve their mechanical properties. Positive effects can manifest themselves in the strength, stiffness, and resistance to failure of the materials. Understanding these properties may lead to the creation of more reliable and durable building materials for various objects and structures.

3.5.2. Thermal Properties

Enhancing the thermal properties of building materials is crucial for efficient energy utilization and ensuring comfort inside structures. Factors such as heat transfer, thermal insulation, and thermal stability greatly influence the performance of materials. One approach to improving these properties is through the incorporation of Carbon Nanotubes (CNTs).

CNTs possess exceptional thermal conductivity, and when integrated into materials, they can significantly enhance their ability to conduct heat. This improved thermal conductivity facilitates better temperature control within buildings, leading to reduced heating and air conditioning costs. By introducing CNTs, the overall thermal conductivity of the material increases, leveraging the exceptional thermal conductivity of CNTs themselves.

Consequently, the use of CNTs in building materials enhances their thermal properties, enabling more efficient utilization of energy resources and improving comfort levels indoors. Additionally, CNTs exhibit high thermal stability, resulting in increased thermal stability of the building materials. This enhancement improves the overall performance and prolongs the service life of the materials. For example, concrete structures containing CNTs display enhanced resistance to fire and other hazards due to their improved ability to withstand higher temperatures.

Shin et al.[476] discuss the development of three types of thermoplastic polyurethane composites (TPU) based on carbon nanotubes (CNTs) to create lightweight, flexible, and heat-conducting materials for electromagnetic interference (EMI) protection. The composites were developed using a solution blending technique with non-solvent induced phase separation (NIPS). The study investigates the impact of CNTs of different lengths on EMI shielding, electrical conductivity, and thermal conductivity. The composite with long CNTs (10 wt.%) demonstrated remarkable EMI shielding efficiency of 42.5 dB and an electrical conductivity of 1.9 × 10-3 S/cm, while the composite with short CNTs exhibited a thermal conductivity of 0.51 W/mK, with a thermal conductivity enhancement exceeding 145% compared to pure TPU. The inclusion of long-length CNTs facilitated the formation of interconnected conductive networks within the TPU matrix, improving mechanical properties, EMI shielding, and electrical properties. Conversely, short CNTs showed significant electromechanical characteristics and heat transferability. The composites also demonstrated high sensitivity to electrical conductivity and minimal changes in EMI shielding effectiveness during repeated bending cycles. This study provides insights into different types of CNT-based TPU composites for superior EMI protection and thermal regulation in next-generation wearable and stretchable electronics.

Table 6. Thermal properties of building materials with CNT

Material	Thermal properties without CNT	Improved thermal properties using CNTs
Polymer composites [478–483]	May have limited thermal stability	The use of CNTs significantly improves thermal stability, reduces thermal conductivity and increases material strength
Ceramics [484–489]	Has high thermal resistance, but often does not have high strength	Use of CNTs increases material strength and thermal resistance
Metals [490–493]	Can have relatively high thermal conductivity and low thermal stability	Use of CNTs increases material strength and thermal resistance
Concrete [494–500]	Has low thermal stability and limited strength	The use of CNTs can increase the strength of the material and improve its thermal stability
Glass [501–506]	Fragile material that does not have high thermal resistance	The use of CNT significantly increases the strength of the material and its thermal stability

In another related study of Jin et al. [477], the development of highly thermally conductive polymer composites with excellent dielectric and mechanical properties for electronic devices is discussed. The researchers incorporated boron nitride, graphene nanoplatelets, and carbon nanotubes into a polycarbonate matrix to enhance thermal conductivity, dielectric constant, and mechanical properties. The resulting composite exhibited a 647% increase in thermal conductivity, a 50-fold increase in dielectric constant, and improvements in yield strength, elongation at break, fracture toughness, and notched impact strength. Moreover, the composite displayed reduced ignitability and remarkable anti-dripping performance. This research presents an effective strategy for fabricating dielectric thermal conductive polymer composites with excellent properties for electronic devices.

Furthermore, incorporating CNTs in building materials can increase their heat capacity. This feature is particularly advantageous for constructing structures capable of absorbing and storing heat, effectively reducing heating costs. Overall, the utilization of CNTs in building materials offers several benefits, including efficient energy utilization and improved comfort within buildings.

To further illustrate the impact of enhanced nanotechnology (CNTs) on thermal properties, Table 6 provides information on various materials. The table includes five different materials: polymer composites, ceramics, metals, concrete, and glass. Each material is presented with its thermal properties before and after the incorporation of CNTs. The first column displays the material names, while the second and third columns present the respective thermal properties before and after the inclusion of CNTs. The table also includes various parameters related to the thermal properties of the materials.

3.5.3. Electrical And Magnetic Properties

The introduction of CNTs into construction materials can lead to a change in their electrical properties. This is due to the fact that CNTs have high electrical conductivity. For example, in the work [507] experiments were conducted on cylindrical concrete samples containing different CNT content up to 0.04%, in which the effect of an alternating magnetic field on the strength was evaluated. Magnetization of samples containing 0.02% CNT gave higher strength than the introduction of 0.04% CNT without magnetization.

By the authors [508] studied the effect of temperature and water content on the electrical conductivity of cement mortar with different sizes of carbon nanotubes and revealed the effect of CNT size on the electrical conductivity of cement mortar. The results show that small diameter CNTs best improve the electrical conductivity of cement mortar. The electrical conductivity of cement mortar with different diameters of carbon nanotubes positively correlates with water content, and as the diameter of carbon nanotubes in the sample decreases, the effect of water content on the electrical conductivity of carbon nanotube cement mortar becomes less.

Corrosion resistance. CNTs can improve the corrosion resistance of construction materials such as metals, concrete and ceramics. CNTs can be added to building materials in the form of a nanofiller that forms a protective layer on the surface of the material. This layer prevents water, acids and other aggressive media from penetrating the interior of the material and protects it from corrosion [509,510]. Table 7 presents the results of studies related to the introduction of CNTs into various materials. Various materials such as concrete, epoxy, wood, rubber, brick, ceramic, steel and asphalt coating were investigated with respect to their properties after the introduction of CNT in different concentrations.

Recent research findings have demonstrated the positive impact of incorporating carbon nanotubes (CNTs) into various materials. This inclusion has led to enhancements in mechanical properties, as well as safeguarding against corrosion and fungal growth. However, determining the optimal concentration of CNTs in each material necessitates further investigation. These research outcomes serve as a foundation for subsequent studies and the optimization of materials containing CNTs. The integration of CNTs can substantially enhance the properties of diverse materials, ultimately contributing to the development of more robust and secure structures in the future.

The utilization of CNTs in building materials holds both economic and environmental advantages. On one hand, CNTs can augment the properties of construction materials, rendering them stronger, more corrosion-resistant, wear-resistant, and durable. Consequently, this can significantly diminish the costs associated with repairing and replacing such structures, thereby proving cost-effective. Additionally, CNTs can enhance the thermal characteristics of materials, facilitating energy savings and reduced expenditures on heating and air conditioning.

Nevertheless, the production of CNTs can be expensive and resource-intensive, potentially escalating the costs of CNT-infused building materials. Moreover, it is crucial to consider environmental factors, such as the ecological and health impacts of producing and utilizing such materials. Certain methods employed in CNT production may generate hazardous waste, emissions, and even disrupt ecosystems. Consequently, economic and environmental aspects must be carefully evaluated when employing CNTs to strengthen building materials. Striking a balance between economic efficiency and environmental safety is imperative when selecting construction materials.

Table 7. Construction materials with CNT

Material	CNT content	Short Description	Source
Concrete	0.10 wt.%, 0.15 wt.%	CNTs have been found to slow the propagation of microcracks by forming bridges through microcracks in concrete.	[511]
	0, 0.03, 0.08, 0.15, 0.25 wt%	The results showed that concrete prepared with high CNT content of 0.15 and 0.25 wt% increased flexural strength by more than 100% compared to concrete with 0% CNT.	[512]
	0.03 to 0.5 wt%	The results showed that 0.03% CNTs with long-term treatment increased the compressive, flexural, and tensile strength of conventional concrete by 23, 29, and 20%. The analysis also showed that using less CNTs (0.03 and 0.08 wt%) gave higher strength results regardless of the nanofiber treatment.	[513]
	0.05-0.1 wt%	It has been demonstrated that 0.05-0.1% CNTs effectively improve the tested properties, increasing the compressive, bending and cleavage strength as well as the fracture energy and modulus of elasticity by up to 23%, 18%, 27%, 42% and 15%, respectively.	[514]
	0.01, 0.02 , 0.03 wt%	The results of the experimental work showed that the introduction of CNT led to an increase in the compressive and tensile strength of the samples compared with the control sample.	[515]
Epoxy	0.107, 0.213 and 0.425 vol.%	The maximum synergistic effect of carbon and ceramic fillers on the dielectric properties of the epoxy-based composite was detected at a CNT content of 0.213 vol.%.	[516]
	0.1, 0.5 and 1 wt%	The results showed that the greatest improvement in the mechanical properties of the CNT/epoxy resin composite was observed in the sample with 0.5 wt% CNT, which had a tensile strength of 61 MPa and Young's modulus equal to 1.8 GPa.	[517]
	0.50 wt%	The tensile strength and toughness of epoxy nanocomposites with 0.50 wt% MWNTs improved by 21% and 46%, respectively, compared to conventional epoxy.	[518]
Wood	0.2%	Antifungal tests showed that stronger growth inhibition was obtained for samples treated with 0.2% MWNT_ZnO + solution. The most effective treatment is a concentration of 0.2% nanocomposite applied with a brush. Thus, protection of wood against mold and fungi was achieved, while providing improved mechanical strength and water protection properties.	[519]
Silicone Rubber	1.25, 5.5, 7.5, 9.5 wt%	The results show that the proposed mixed carbon nano conductive silicone rubber has good properties and great application prospects.	[520]

Material	CNT content	Short Description	Source
Brick	0.01%	The compression strength of the MUNT-added bricks was 53.9% and 45.52% higher compared to commercially available and traditional bricks.	[521]
Ceramics	0.1, 4 wt%	The thermal conductivities of nanocomposites with different amounts of carbon nanotubes (0, 1 and 4 wt%) were investigated. Thermal conductivity increases with increasing temperature, 1 wt% CNT/silica nanocomposite provides the highest thermal conductivity.	[522]
Steel	0.05, 0.1, 0.3, 0.5 wt%	Among all the samples tested, the lowest corrosion rate was achieved at 0.1 wt% CNT nanofluid, while the highest value was obtained at 0.5 wt% CNT nanofluid. At higher CNT concentrations, the accumulated CNTs can form active anode sites and increase the corrosion rate.	[523]
	0.2, 0.5, 1.0, 2.0 wt%	The composite samples showed increased wear resistance compared to the primary and commercial grades.	[524]
Asphalt surface	0.1, 0.5, 1 wt%	The study demonstrates that the introduction of CNT into asphalt cement improves asphalt concrete performance in both hot and cold weather, which in turn extends pavement life and saves maintenance costs.	[525]

Therefore, the utilization of CNTs to reinforce building materials represents a promising frontier in modern engineering. This technology presents unique opportunities to enhance material properties, including strength and fracture resistance. However, the successful implementation of this technology necessitates further research on the economic and environmental efficiency of producing and employing CNT-infused materials. Overall, the integration of CNTs in building materials instills hope for the creation of more durable and safer structures in the future.

3.6. Challenges and Future Directions in CNT Applications for Building Materials

The production and application of Carbon Nanotubes (CNTs) in building materials face several significant challenges. While CNTs hold immense promise for revolutionizing the construction industry, these challenges must be addressed for their widespread adoption. Here are some of the key issues:

- Large-Scale Production and Cost: Achieving large-scale production of high-quality CNTs at a reasonable cost is a major challenge. Current methods, like chemical vapor deposition (CVD), have issues with efficiency, high synthesis temperatures, and limited control over properties.
- Control of CNT Growth: Precise control over the growth process is needed to prevent the formation of unwanted carbon structures alongside desired CNTs, as these impurities can affect properties of construction materials.
- Uniform Dispersion: Ensuring uniform dispersion of CNTs within construction materials is crucial. Agglomeration can affect mechanical performance and poses health and safety risks to workers.
- Interface Bonding: Establishing a robust interface between CNTs and the matrix is essential for maintaining mechanical strength.
- Health and Safety Risks: The potential health and safety risks associated with CNTs must be carefully managed.

- Long-Term Stability and Durability: Evaluating the long-term performance of CNT-based composites under different environmental conditions is crucial to ensure durability.
- Cost-Effectiveness: The high cost of CNTs, processing steps, and potential alterations needed for large-scale production can impact economic feasibility.

To overcome these challenges and fully realize the potential of CNT-based building materials, recommendations for future research and development include:

- Optimization of CNT Dispersion Techniques: Investigate innovative dispersion methods to prevent agglomeration, such as functionalization, surfactants, and advanced mixing techniques.
- Enhancement of Interfacial Bonding: Develop strategies for improving the bond between CNTs and the matrix to optimize mechanical properties.
- Scalable Production Processes: Explore cost-effective synthesis methods and processing approaches that can be scaled up without compromising CNT quality.
- Safety and Environmental Impact Assessment: Thoroughly assess health and safety risks, develop safety protocols, and conduct environmental impact assessments.
- Multifunctional Material Development: Explore the potential for multifunctional CNT-based building materials, such as self-healing, self-cleaning, or thermal regulation capabilities.
- Long-Term Durability Studies: Conduct studies to evaluate the long-term stability and durability of CNT-based building materials under various environmental conditions.

4. Conclusions

CNTs have exceptional mechanical properties, making them attractive for construction. Adding CNTs to concrete enhances its strength and durability. However, challenges include higher material costs and the need for specialized methods to ensure proper distribution. Establishing standards and regulations for safety and reliability is crucial. Further research will determine better techniques for incorporating CNTs into building materials. Utilizing CNTs in construction has the potential to create more resilient structures.

The optimal concentration of CNTs to enhance the properties of different materials is also a crucial consideration and may vary depending on the material type and desired characteristics. Here are a few examples:

Polymeric materials: For polymers like polyethylene or polypropylene, an optimal concentration ranging from 0.5% to 5% is typically recommended. This concentration range achieves improved mechanical properties such as strength and stiffness, along with enhanced thermal and electrical conductivity. In the case of elastomers, such as rubber materials, the optimal CNT concentration is generally lower, usually between 0.1% to 1%, which enhances the elastic and mechanical properties, such as resistance to rupture and deformation.

Metallic materials: In the case of metals like aluminum or iron, the optimal concentration of CNTs typically falls within the range of 0.5% to 2%. Incorporating CNTs within metallic materials can enhance their strength, hardness, thermal conductivity, and electrical conductivity. It is also important to ensure proper dispersion of CNTs in the metal matrix to achieve homogeneity and uniform reinforcement of properties.

Ceramic materials: When it comes to incorporating carbon nanotubes (CNTs) into ceramic materials such as oxides, carbides, or nitrides, it is recommended to add them in the range of 1% to 10%. While this range can enhance properties such as strength, hardness, thermal conductivity, and dielectric properties, it is important to carefully consider the potential drawbacks. The use of a high concentration of 10% CNTs in ceramic materials can lead to increased brittleness, affecting the material's integrity and processing. Additionally, it should be noted that such a high concentration may also significantly impact the overall cost of the material. Given these considerations, it would be advisable to reassess and fine-tune this concentration range to strike a balance between material properties and cost-effectiveness.

The optimal concentration of CNTs can vary based on specific conditions. Further studies and laboratory experiments will aid in determining the optimal CNT concentration for particular materials. Advancements in catalyst development play a significant role in improving the chemical vapor deposition (CVD) process for producing high-quality CNTs. Catalysts influence the growth, structure, morphology, and properties of CNTs. One approach involves employing novel catalysts based on metals or alloys such as nickel, iron, cobalt, molybdenum, and their compounds. These materials exhibit high activity and stability, contributing to more efficient CNT growth. Precious metal-based catalysts like platinum or palladium are also being explored to enhance CNT quality and achieve higher-quality single-layer and defect-free growth.

A comprehensive examination of catalyst shape and structure is crucial to optimize the CVD process and improve CNT quality. Studies have shown that the use of nanostructured catalysts, such as nanoparticles, nanowires, or nanofilms, facilitates more uniform and controlled CNT growth. Additionally, modifying the catalyst's surface with layers of other materials like oxides or carbides has been considered. This approach helps improve catalyst adhesion and stability, while also providing control over CNT growth. Optimizing the gas mixture composition used in the CVD process can significantly impact CNT growth and quality. The addition of different gases, such as hydrocarbons, inert gases, or decomposition intermediates, aids in controlling growth rate, structure, and dispersion of CNTs.

Practical applications of CNT-reinforced materials in construction include:

Concrete composites: CNTs can be employed to reinforce concrete, creating composite materials with high strength and resistance to breakage. This leads to improved mechanical properties of concrete.

Reinforcement of metal structures: Introducing CNTs into metal materials enhances their mechanical properties, such as strength and stiffness, thereby improving the reliability and durability of structures.

Heat and sound insulation: The use of CNTs in construction has the potential to improve heat and sound insulation properties. Despite encountering technical challenges, the utilization of CNTs in construction holds significant potential for creating stronger, more stable, and durable structures. Ongoing research and development efforts will enhance the technology and expand the use of CNTs in construction in the future.

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