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Review

Application of machine learning initiatives and intelligent perspectives for CO_2 emissions reduction in construction

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ABSTRACT

The construction sector is one of the main contributors to carbon dioxide (CO_2) emission and causes of global warming. CO_2 mitigation solutions are vital. New technologies can facilitate and improve these efforts. Thus, the paper reviews how new technologies of artificial intelligence and machine learning have contributed to CO_2 emissions reduction in construction and what techniques have been applied in the literature to provide significant information that will be beneficial for the construction sector design and management. The paper provides the results of a content review, including their contributions and gaps. A total of 78 papers were identified to develop the dataset. The method was a combination of systematic reviews, including co-occurrence analytical map development of the main keywords, co-authorship network analyses, publication source analyses, and content analysis, including theme identification and review of the selected papers, which were divided into five conceptual clusters based on their scopes: (1) sustainable materials and components design/production, (2) on-site vehicles and equipment, (3) energy and life cycle assessment, (4) optimization, decision-making and solution-based platforms, and (5) real-world monitoring. The content of each cluster of papers was also reviewed, and the potential gaps were identified and discussed. A set of directions for future research investigations were presented that can be a valuable source for researchers in their future research. This paper contributes to the current knowledge base by presenting insights into intelligent techniques in the construction industry to mitigate CO_2 emissions.

1. Introduction

Carbon dioxide (CO_2) emission, as one of the major components of greenhouse gases (GHGs), plays a vital role in global warming, which is one of the most important environmental issues that threatens the life of the creatures in the world (Camp and Huq, 2013). The construction industry is one of the main sources of CO_2 emissions (Mazurana et al., 2021). In this regard, there is an urgent need to mitigate CO_2 emissions (Costa and Ribeiro, 2020; Bigyeong and Sumin, 2022) in all industries, including construction (Lee et al., 2020; Liu et al., 2021a). The construction industry, accounting for up to 50%, is the largest source of GHG emissions globally (Mirmozaffari, 2021). Many research studies have addressed global warming concerns and the potential to mitigate CO_2 emissions in different stages of the construction process, i.e., pre-construction, construction, use phase, and even post-disaster temporary housing and reconstruction (Robles et al., 2022; Hosseini et al., 2021; Farahzadi et al., 2016). The concrete industry is one of the most pollution-oriented sectors in construction; cement production is estimated to contribute to almost 8% of global warming emissions (IPCC, 2006).

Technology can affect CO_2 emissions in both positive and negative ways. Recently intelligent technology/technique has been rapidly progressing, and more of its application has been examined in the construction sector in the direction of sustainability and emission reduction by researchers and practitioners (Karimi et al., 2021b; Sepasgozar et al., 2020). By transforming traditional to new construction technologies, materials, and automated practices in both hardware and soft computing aspects, there would be great potential for CO_2 emissions reduction in the construction industry. Internet of things (IoT), artificial intelligence (AI), real-time monitoring, machine learning (ML), and optimization methods are among the novel practices in which the globe is shifting its direction.

AI and ML promote more automated and accurate decision-making, prediction, and optimization in construction processes and activities.

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Several papers have addressed using new technologies- AI and ML-for CO_2 emission reduction in construction (Yang et al., 2021; Peng, 2019; Cho et al., 2015). Most studies investigated designing and producing sustainable and environmentally friendly building materials (Trinh et al., 2021; Naseri et al., 2020; Kordnaeij et al., 2019b). This particularly applies to the cement and concrete industry (Narasimha Reddy and Ahmed Naqash, 2019; Park et al., 2016) as the most pollution-driven sector (Zhang et al., 2021; Van Tonder and Low, 2021). Sojobi and Liew (2022) conducted a laboratory-based examination and response surface methodology to design and produce a bioinspired sandwich carbon-fiber reinforced polymer that uses concrete wastes as aggregates. Faridmehr et al. (2021b) used an optimized artificial neural network (ANN) to investigate concrete mixes using less cement by replacing it with fly ash (FA) and more sustainable materials. Alaneme and Mbadike (2021) applied fuzzy logic to investigate the optimized concrete mixes replaced partly by palm bunch ash and bentonite. On the other hand, several papers examined CO_2 emission reduction on the construction sites for on-site vehicles and equipment as they emit a significant amount of carbon. They tried to optimize the fuel and the activities of such vehicles (Jassim et al., 2019; Trani et al., 2016; Peng et al., 2016). Jassim et al. (2019) presented an ANN-based model integrated with a perception multilayer to predict the fuel usage of wheel loaders when hauling materials. Life cycle assessment (LCA) (Thilakarathna et al., 2020; D'Amico et al., 2019) and real-world monitoring (Karimi et al., 2021a; Liu et al., 2020) are among other directions which some papers have addressed. Alabduljabbar et al. (2020) conducted LCA on different concrete mixes, which calculated mechanical properties using optimized ANN. Liu et al. (2020) presented a sensor-based real-time system for recording and visualizing emissions for three on-site equipment in prefabricated construction sites. All these studies denoted that CO_2 emissions from the construction sector are high, yet disregarded, implying the need for enhanced tools and methods for mitigation and decision-making beyond the current and traditional trends. The existing literature illustrates a vast perspective of the AI and ML contribution to CO_2 reduction in construction. As there is no specific overview, to the best of the authors' knowledge, there is a need to review the previous investigations holistically to provide a thorough picture of the ongoing research. This paper mainly aims to determine the directions of the previous research studies and to identify limitations, gaps, and future research potentials in this area. The initial step is to identify related articles in a systematic manner. Then, bibliographic and content analyses are conducted to evaluate the related articles thoroughly. This involves classifying the concepts of CO_2 emission mitigation using AI or ML techniques into different clusters. Finally, the paper analyzes the gaps and develops directions for future investigations.

2. Research methodology

2.1. Review method

The method of this review is designed according to two research questions: *(1) in what directions AI and ML are used in construction to reduce CO_2 emissions?* and *(2) what AI and ML techniques are applied to contribute to CO_2 emissions reduction in construction?* A systematic review is conducted to find the relevant articles to address these questions. The gathering and filtering method for the articles' literature is a vast, top-down approach that collects articles using broad phrases first and then excludes those that may be irrelevant to the research. The methodology consists of the following steps: (1) categorizing the research questions and inclusion and exclusion criteria; (2) collecting relevant articles through systematic search, screening, and filtering the articles regarding the inclusion and exclusion criteria; (3) gathering relevant information from the included articles; a bibliographic analysis is presented that targets to illustrate a quantitative analysis to investigate the trends of academic publications. (4) categorizing and analyzing the significant findings; the paper deeply reviews and categorizes the existing relevant literature into different research directions. Each direction is analyzed by content, then, its significant findings, gaps and future research are addressed.

2.2. Data extraction

The systematic content review on the applications of AI and ML for CO_2 emissions reduction in construction was designed as a five-step research protocol. This method included the establishment of a review protocol, (1) database selection, (2) search string design, (3) exclusion and inclusion criteria, (4) relevant publications filtering, and (5) review and analysis. No time interval was considered in the review protocol. Fig. 1 illustrates the method followed for selecting the relevant articles.

The literature was searched through Web of Science and Scopus databases in the first step. The following combination of keywords (*Emissions* AND (*CO_2* OR *carbon*) AND *construction* AND ("*artificial intelligence*" OR *AI* OR *intelligent* OR *smart* OR "*machine learning*" OR *ML* OR *IoT* OR "*internet of things*")) were used in the second step to search the relevant literature. As a result, 678 papers were identified. In the next step, to decide the eligibility of the detected papers for inclusion, several criteria were considered: (1) peer-reviewed journal papers, (2) papers in English, and (3) papers related to the construction of buildings and bridges. This led to 345 papers. After eliminating the 96 duplicated papers in the fourth step, 249 papers remained. In the last step, titles and abstract screenings were carried out, and 118 papers were kept. The full article review retained 78 papers for the scoping review. Based on the remained papers, bibliographic analysis, statistics of the literature, and content analysis were conducted.

3. Bibliographic analysis

In this part, the bibliographic analysis of the reviewed papers is shown in different dimensions based on the publication source, authors and keywords through various charts and tables.

3.1. Analysis of articles according to publication source and year

There is an increasing trend in the number of articles on the application of AI and ML for CO_2 emissions reduction in construction published in academic journals from 2012 (Fig. 2). Table A in the Appendix shows the sources of the published articles in academic journals each year. In total, forty-three academic journals were identified. Journal of Cleaner Production has contributed to the highest publication proportion. Journal of Construction and Building Materials is on the second rank. Fig. 3 shows the publications per year per source for the top 7 journals. Journals of Automation in Construction, Construction Engineering and Management, Energy and Buildings, and Materials stand next. The distribution of the articles by country is illustrated in Fig. 4a and b, where 26 countries were identified. China has the highest rank (18.5%), followed by the USA (12.3%) and South Korea (11.1%). Iran (7.4%), Australia (7.4%), and Spain (6.2%) are in the next places for having the highest publications in this area.

3.2. Analysis of articles according to co-authorship

The total number of authors is 264. Fig. 5 shows the total strength of co-authorship density and network with 234 authors and the co-authors with at least two links to other authors. Thus, 30 authors having fewer connections were not included. As the directions in CO_2 emissions reduction with the help of AI and ML may vary with specific expertise in each area, the connection of authors is distributed in different small groups without having a more robust network within certain larger groups. The most extensive set of connected items consists of 13 authors, shown in Fig. 6. Most are from Chine, one is affiliated with academic institutions in the UK, and one is in Singapore. It is noteworthy to mention that 25.7% of the articles were carried out through

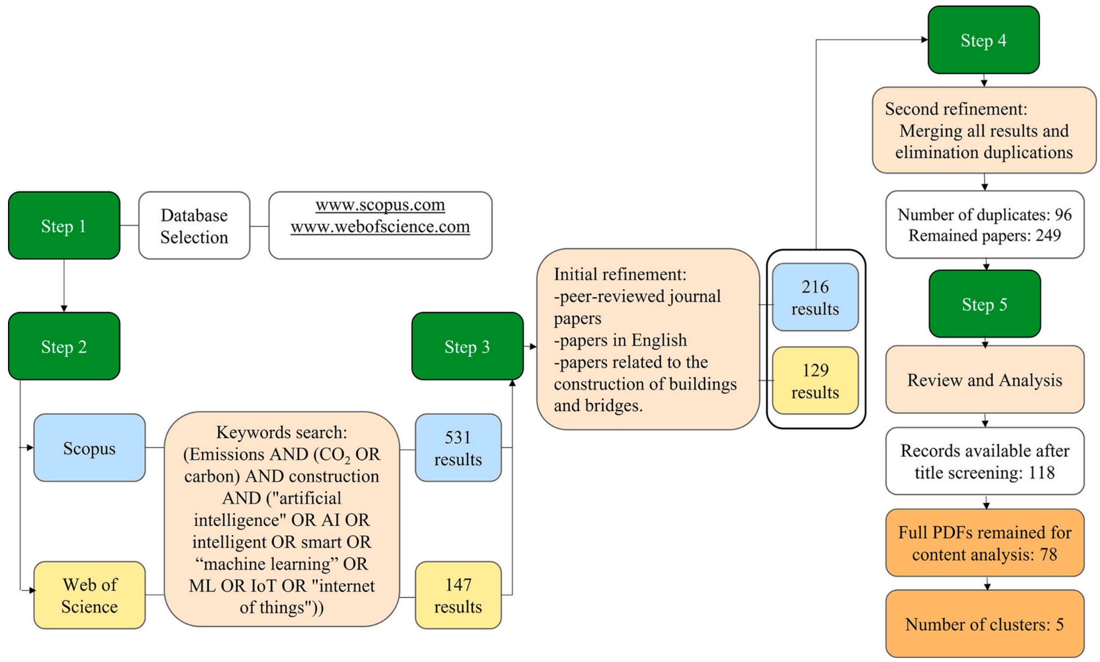

Fig. 1. Literature screening and paper inclusion process.

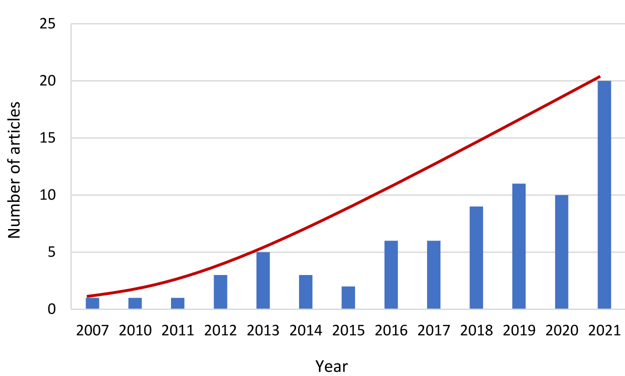

Fig. 2. The number of articles per year, based on the search result.

international collaborations. Scholars in Australia have the most international collaborations (31.6%) among others.

3.3. Analysis of articles according to the network of keywords

The analysis map of keywords co-occurrence based on the initial bibliographic data set is shown in Fig. 7. The analysis map helps identify the common themes in CO_2 reduction using AI and ML. The figure shows the themes such as concrete and cement, compressive strength (CS), optimization, onsite vehicles, LCA, etc., as high-frequently used. Thus, the content review and concept categorization in section 4 are based on the keywords analysis map and the occurrence and relationship of the keywords.

4. Content review and systematic analysis

4.1. Main concepts

After carefully assessing, five main directions were formed out of the bibliometric analysis. The concepts identified in the literature related to the initiatives to reduce CO_2 emissions in construction using new technologies of AI and ML techniques have been categorized into (1) sustainable materials and components design/production, (2) on-site vehicles and equipment, (3) energy and life cycle assessment, (4) optimization, decision-making and solution-based platforms, and (5) real-world monitoring; see Fig. 8. In sections 4.1.1. to 4.1.5., all the concepts are discussed, then the gaps and future research directions are elaborated.

As illustrated in Fig. 8, different ML techniques have been applied in each cluster. Some of these ML methods were more frequently used. Fig. 9 shows the top-used ML techniques in the existing literature. Genetic algorithms (GA) and regression are mostly used to find solutions to reduce CO_2 emissions in construction. Neural networks, support vector machine (SVM) and random forest (RF) come next, respectively.

4.1.1. Sustainable materials and components design/production

4.1.1.1. Sustainable materials design/production. Concrete and cement production are among the most pollutants industry. Many efforts have been made to reduce their impact by replacing more sustainable materials in the concrete design components (Dabiri et al., 2022; Kandiri et al., 2021) and predicting their properties using ML techniques (Kioumarsi et al., 2020; Plevris et al., 2022).

Long et al. (2021) used calcined clay, limestone powder, silica fume, as cement substitutes for a low-carbon and low-energy 3D printable composite. Particle packing theory for the optimization of the packing density of the particle components through the particle size distribution was applied. The results showed that the dynamic yield stress can be significantly improved when composites contain 33 wt% calcined clay, 16.6 wt% limestone powder, and 5 wt% silica fume with a sand to binder ratio of 2.5. Wimala et al. (2019) introduced an ANN-based model to predict CO_2 emissions from producing precast concrete. First, a survey was carried out for 107 precast concrete plants in Japan to acquire data on the CO_2 emission factors. Six factors of ordinary Portland cement (OPC), fine aggregate, coarse aggregate, electricity, kerosene, and heavy oil, were considered using Principal Component Analysis to serve as the inputs for the ANN model to predict CO_2 emissions. A backpropagation neural network technique with three-layer perceptron was introduced to train the network. The network model having 51 hidden neurons with a set of 0.1, 0.3, and 0.9 for learning rate, initial weight, and momentum, respectively, generated the best result. Mean absolute percentage error

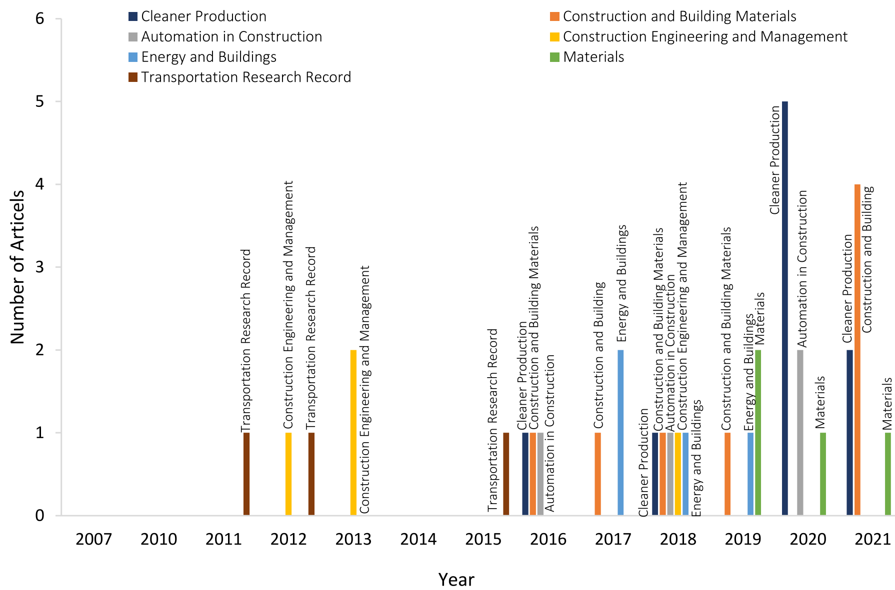

Fig. 3. Publications per year per source (top 7 journals).

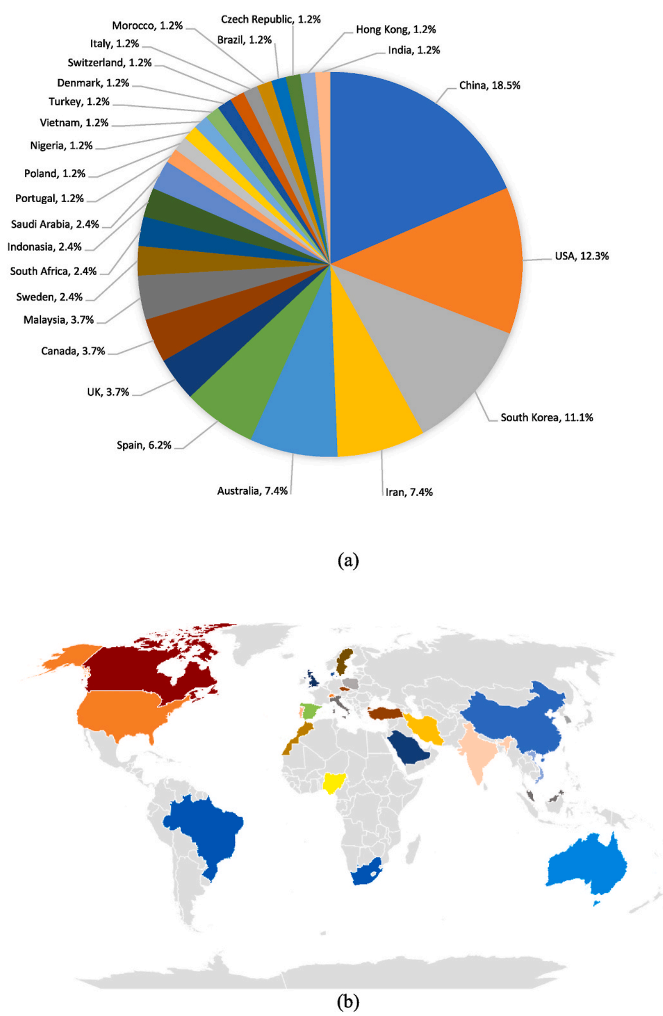

Fig. 4. The distribution of the 78 journal articles by country (a) pie chart, and (b) world map.

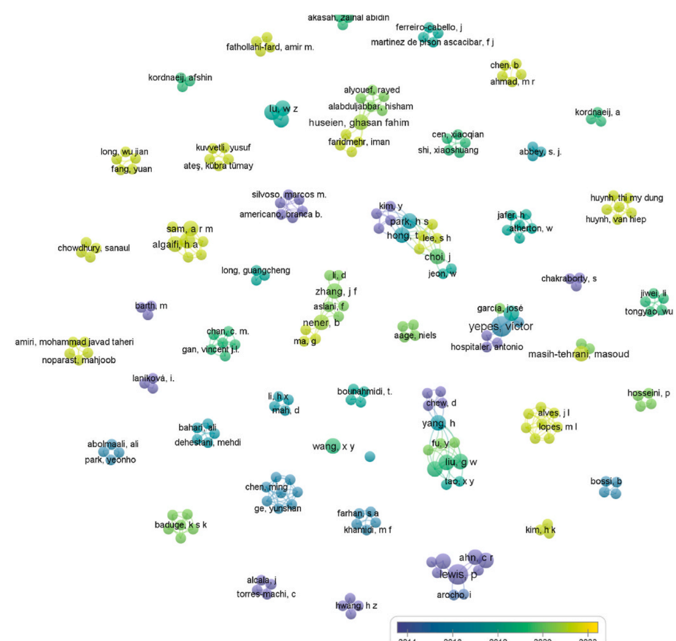

Fig. 5. Visualization of co-authorship network for the 234 authors based on the full counting technique.

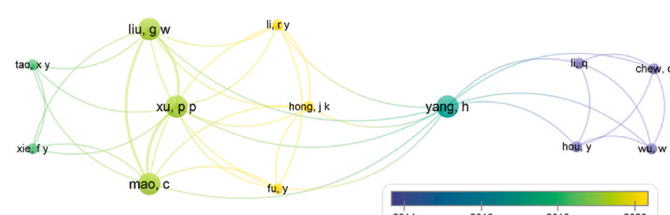

Fig. 6. Visualization of the largest co-authorship network comprising 13 authors.

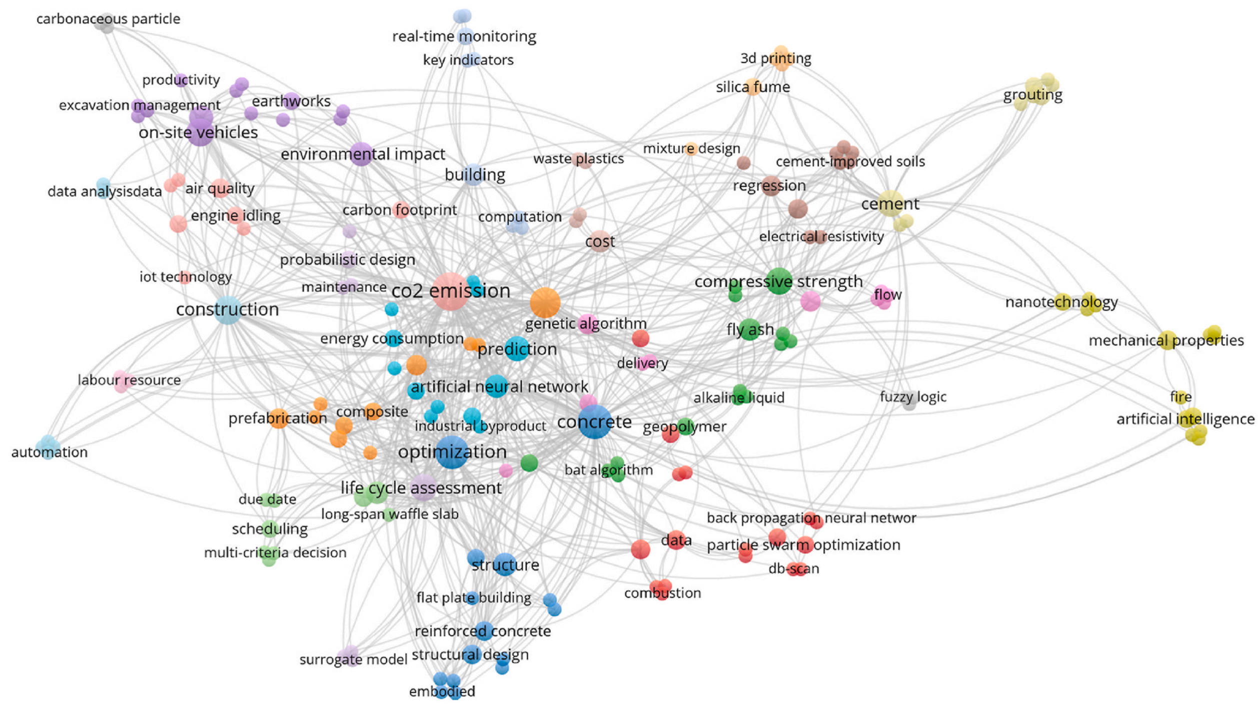

Fig. 7. Co-occurrence analytical network of keywords identified in the relevant search result. All 190 identified keywords are included.

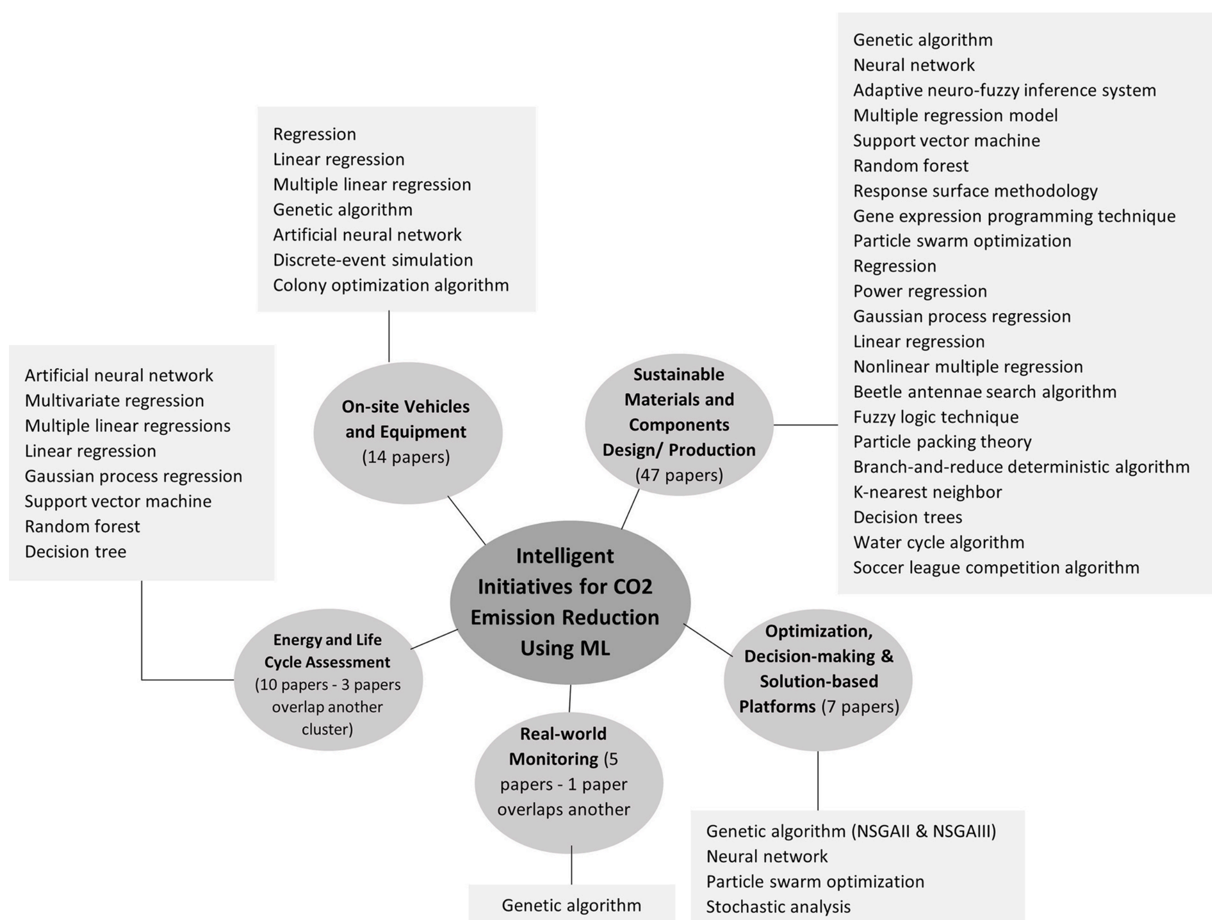

Fig. 8. Concept categorization of CO_2 emissions reduction initiatives in construction using ML techniques based on the co-occurrence analytical network of keywords identified in the relevant search results.

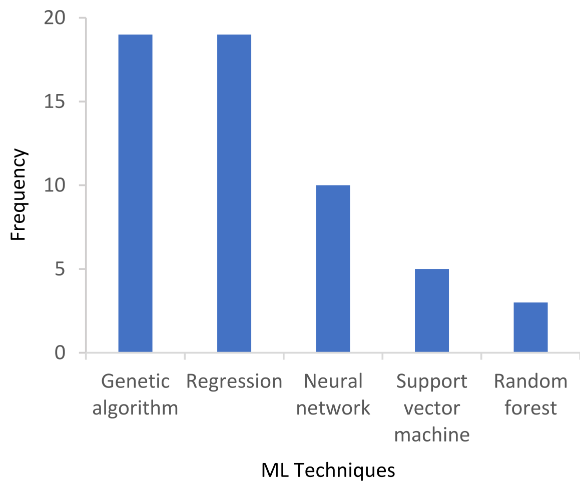

Fig. 9. Top-used ML techniques in the existing literature regarding CO_2 emissions reduction in construction.

(MAPE) value below 10% revealed that ANN could predict CO_2 emissions in producing precast concrete with significant accuracy. Huseien et al. (2021) examined substituting cement with different percentages of FA and effective microorganism (EM) under various water to binder ratios (w/b) to achieve an optimized proportion to produce sustainable concrete with lower CO_2 emission and boosted mechanical properties. An adaptive neuro-fuzzy inference system (ANFIS) was employed to test the CS of the laboratory-based database. The results revealed that the optimal mixture obtained for the specimen with OPC replacement with 10% FA and EM operated optimally led to CS of 50 MPa, 41% lower carbon dioxide, 40% less energy consumption, and 25% lower cost.

Other studies investigated partially replacing cement with zeolite. Kordnaeij et al. (2019a) employed multiple linear regression (MLR) and a kind of ANN named GMDH (group method of data handling) to predict the small strain shear modulus in zeolite–cement grouted sands. The small strain shear modulus function included three w/b ratios, average sand grain size, and cement replacement with zeolite percentage. The results revealed that MLR and GMDH techniques for predicting small strain shear modulus of grouted sands perform better when considering active compounds as an input factor than considering w/b and zeolite percentage as input factors. Furthermore, the GMDH-based model performed more efficiently than the MLR-based one. In another study, Kordnaeij et al. (2019b) conducted a lab-based study to examine the impact of several factors on the CS of the specimens, including sand size, w/b, and cement replacement percentage with zeolite. MLR and a GMDH-type neural network were applied to predict the CS of zeolite-cement grouted sands.

Ma et al. (2018) applied a highly effective stabilizer based on cement and embedded FA to create a more environmentally friendly earth-based construction. Several parameters, such as FA content, stabilizer content, physical indexes, and curing duration, were considered to conduct a hybrid strength and embodied CO_2 index measurement. MLR and power regression methods were employed in this study. The results revealed that cement-based high-efficiency stabilizer is cleaner than cement, even though several chemical additives have higher CO_2-equal emissions. Abbey et al. (2017) replaced partial cement with ground granulated blast slag (GGBS) and pulverized fuel ash (PFA) for deep soil concrete to improve CS and reduce CO_2 emission. Different mixes of cement, cement with PFA, and cement with PFA and GGBS were tested at different ages. MLR was used for the prediction of the unconfined compressive strength (UCS). Soil with less plasticity indicated greater CS than soil with higher plasticity. Adding GGBS and PFA reduced the cement content, reducing cost and CO_2 emissions. The proposed method provided reliable and accurate prediction for CS for weak soil with UCS less than 25 kPa, and the proportion of w/b. The model was validated using different compositions of binders. Ates et al. (2021) applied an ANFIS and an ANN to present a decision-making platform for the activity index prediction of GGBS for producing sustainable cement. A test duration of 28 days is required to obtain the activity index of GGBS, which involves the product's quality, cost, and environmental effects. Thus, for the optimum status, durations of 2- and 7-day activity index determination are needed. As a result, a decision-making platform for this prediction environment based on machine learning techniques was developed through a dataset containing 1,021 data. The ANN results assessed the MAPE value for the total data set of 2.27%. ANN showed more superiority than the ANFIS method. The developed decision support system assisted in the optimal determination of the composition and made CO_2 emission reduction in the process of slag cement (CEM III) production.

Apart from FA, zeolite, and GGBS, some studies investigated replacing cement with other recycled materials or byproducts. Park et al. (2016) investigated the potential application of crumb rubber made from recycled tires in geopolymer concrete to diminish cement content, which leads to CO_2 emissions reduction. The effects of aggregate size and amount, the molarity of sodium hydroxide, the curing method, and time parameters on CS were examined. Sodium silicate, sodium hydroxide liquid mix, FA, and crumb rubber were utilized in the geopolymer concrete. The regression model was applied to recognize the effect of essential parameters and their interactions on the strength of geopolymer concrete. It showed that the relationship between rubber substitution and other factors was insignificant. The ANOVA technique showed that the best proportion for crumb rubber is 5%, with a 95% confidence level in three kinds of FA. A suitable proportion of rubber substitution could be applied without significant strength reduction. Fairbairn et al. (2010) replaced cement with sugar as a by-product at industrial level to reduce CO_2 emissions. Sugar cane bagasse ash is a pozzolan that can be used as a substitution for cement to boost the cement-based mixture properties. A simulation based on the United Nations Framework Convention on Climate Change for the Clean Development Mechanism was conducted to assess the possibility of CO_2 emission reduction. Because the average distance between cement plants and sugarcane ethanol factories is one of the major variables in estimating CO_2 emissions, a GA model was created to handle this optimization challenge. Over 60% of the country's sugar cane and ash production and a significant number of cement plants—located in Sao Paulo, Brazil—were selected as a case study. In total, around 520 kilotons of CO_2 were estimated to be reduced annually by applying this United Nations Framework approach. Table 1 summarizes the ML techniques applied to design and produce sustainable materials.

4.1.1.2. Sustainable components design/production. Besides sustainable material design, several studies have addressed component design and production (Lee et al., 2021; García et al., 2020; Baandrup et al., 2020). Lee et al. (2021) presented a multi-objective optimization based on NSGA-II algorithm to design waffle slabs with reduced CO_2 emissions and costs. Variables such as slab thickness, concrete CS, rebar diameters, reinforcement yield strength, rebars' place interval, ribs specification, and waffle forms specification were considered for 20 types of waffle slabs. Cost- and emission-efficiency analyses were carried out, and the results were validated on a real waffle slab of Korea Gimpo International Airport. It was shown that waffle form specifications, particularly the ribs height and the distance between ribs, among the design parameters, have the highest impact on optimizing cost and CO_2 emissions. Trinh et al. (2021) introduced a method for carbon-based optimization (minimum CO_2 emissions) of a flat plate reinforced concrete (RC) building using a Branch-and-Reduce deterministic algorithm. Different case studies with varying spans of slab and floor levels were optimized using the Branch-and-Reduce Optimization Navigator commercial package and GA solver of MATLAB. The results showed that the optimized model

Table 1
Sustainable materials design and production using ML techniques.

Authors	Sustainable Materials	Soft Computing Method	Outputs
Kim et al. (2021)	Ocean-borne plastic flakes cement mortar	Regression	- Ocean-borne plastic flakes as fine aggregate (specific gravity: 2.47, water absorption: 3.5) - Not to be used in structural members - The coefficient of the regression model (R^2) was 0.62
Alaneme and Mbadik (2021)	Green bentonite and palm bunch ash concrete	Fuzzy logic technique	- Applying 5% of palm bunch ash and bentonite as a replacement for cement led to the maximum CS, as well, to green concrete with less environmental impact - R^2 of 84.9% and 99.1% was calculated for MLR-model and fuzzy-logic model, respectively
Ahmad et al. (2021)	Hemp-based bio-composite	AI-based gene expression programming (GEP) technique	- The CS and thermal conductivity were mainly influenced by plant aggregate to binder, w/b, and density of bio-composite - Bio-composites absorbed 14- 35 kg/m^3 CO_2 from the environment - The GEP model proved a high R^2 of 0.957 and the lowest root-mean-square error (RMSE: 67.3) compared to other regression models
Zhang, Huang, et al. (2020a)	Recycled aggregate concrete	K-nearest neighbor, regressors, random forest, support vector machine, backpropagation neural network (BPNN), multi-objective optimization model based on AI, and multi-objective firefly algorithm	- RF and BPNN gained the best accuracy for predicting compressive and splitting tensile strength of recycled aggregate concrete, indicated by the highest correlation coefficients (0.91 and 0.84, respectively) and lowest RMSE (6.64 MPa and 0.514 MPa, respectively) - The model successfully optimized the recycled aggregate concrete mixture proportions for the CO_2, cost, and CS trade-offs
Thilakarathna et al. (2020)	High and ultra-high strength concrete	Artificial neural network, Gaussian process regression (GPR), support vector machine, decision trees (DT), and linear regression (LR)	- Several supervised machine learning techniques of ANN, GPR, SVM, DT, and LR were applied to produce new concrete design compositions with low embodied carbon and defined CS. The result of analyzing 700,000 designed compositions revealed that the ANN showed the best function while the LR was the worst - R^2 and RMSE for the ANN algorithm were 0.97 and 5.1, respectively
Naseri et al. (2020)	Sustainable OPC concrete	Meta-heuristic-based technique: six machine learning techniques, including water cycle algorithm, soccer league competition algorithm, genetic algorithm, artificial neural network, support vector machine, and regression	- Water cycle algorithm was selected as the most accurate algorithm with R^2, MAE, MSE, and RMSE of 0.93, 2.8, 13.6, and 3.6, respectively, on the testing set - Six mixtures gained appropriate performance in the trade-off of all defined CS criteria, cost, and environmental impacts (including embodied CO_2 emission and energy and resource consumptions)
Alabduljabbar et al. (2020)	Waste sawdust-based lightweight alkali-activated concrete	Artificial neural network	- The CS of the concrete with 100% sawdust as a replacement for natural aggregates was 48.6 MPa. This formulation decreased CO_2 below 85% fuel production compared to one with natural aggregates - Cubic-shaped molds, cured for 1, 3, 7, 28, 56, and 90 days following the ASTM C579 specification, were applied - Training correlation value of 0.99 and testing correlation value of 0.99 were achieved. The mean error for the training data was noticed as 1.37
Wang and Lee (2019)	Low CO_2 slag-blended Concrete	Genetic algorithm	- Concrete with various strength levels (w/b ratios from 0.20 to much higher), different slag substitute levels (slag replacement ratios from 0 to 80%), and various curing conditions (curing temperatures of 5 °C–80 °C) - Strength development model: the slag substitute ratios were 25%, 50%, and 75%, and CS was measured at 1 day, 3 days, 28 days, and 18 months
Wang (2019)	Low–cost and low–CO_2 blended concrete	Gene expression programming, and genetic algorithm	- Regression was performed on concrete CS at 28 days as a function of the w/b ratio, the FA to binder ratio, slag to binder ratio, and the water content - The correlation coefficient between the analysis results and the experimental results on CS was 0.99
Narasimha Reddy and Ahmed Naqash (2019)	Supplementary cementitious materials	Response surface methodology	- CS, splitting tensile strength, and flexural strength, were investigated - 20% alccofine substitution for cement gained better durability and mechanical properties in comparison to other mixes - The obtained R^2 was 0.99, proving the model's appropriate fit as the discrepancy of whole variation is 0.0027% and was in an acceptable error range. The residual sum of squares (RSS) of 2.12 proved the appropriate fit of the model
Kurpinska and Kułak (2019)	Lightweight Concrete	Artificial neural network	- Six cubic samples for each lightweight concrete were applied - CS test on day 28 - The highest CS was determined with glass ash aggregate ratios of 75% and 100%, with 21.3 MPa and 18.6 MPa - Use of 25% of granulated expanded glass aggregate resulted in about a 13% increase in concrete CS, a 12% decrease in density, and a 15% decrease in porosity

(*continued on next page*)

Table 1 (*continued*)

Authors	Sustainable Materials	Soft Computing Method	Outputs
			- The errors by ANN during testing of ANN's quality on various sets of tests constitute up to 15%
Cen et al. (2019)	Concrete mixture	Adaptive surrogate model, and genetic algorithm	- 15 samples of different types of concrete (C70, C40, and C30) from a concrete plant with 28 days of curing - When the content of FA and phosphorus slag were 99.27, 153 and 113.5 and 191.61, 101.4 and 103 kg/m^3, respectively, cost and CO_2 emissions of C70, C40 and C30 concrete were the lowest - Low normalized RMSE suggested a good model fit
Shubbar et al. (2018)	Environmental friendly cementitious material	Multi-regression model	- GGBS substituted OPC at different percentages: 10–50% by mass of OPC to reduce CO_2 emissions - Three samples of dimensions 40×40×160 mm, two halves by three-point loading of the prism specimens, and averages of six halves were taken to represent the final values for CS - At 3, 7, 28, and 56 days of curing compared with the reference cement samples - Prediction of CS could be modeled with R^2 of 0.89
Yang et al. (2007)	Cementless mortar using hwangtoh binder	Nonlinear multiple regression	- Cement replacement by hwangtoh - Cubes of 50 mm, CS at 1, 3, 7, 14, 28, and 91 days in temperature 23 ± 2 °C and relative humidity of 70 ± 5% - CS increased gradually while increasing the volume fraction of fine aggregate but decreased at a fine aggregate/hwangtoh binder ratio of 3.5 - The standard and mean deviation of the ratio between the predicted and experimental flow were 0.08 and 1.02, respectively

could reduce 5–17% embodied carbon compared to conventional buildings. The proposed method decreased 31% of the total embodied carbon compared to the GA method. An optimized design to reduce the total cost or CO_2 emissions for RC frames based on the guidelines and provisions specified by the American Concrete Institute (ACI) using an integrated Big Bang and Big Crunch optimization (BB-BC) was presented by (Ahn et al., 2013). Two cases of structural frames were chosen to evaluate the efficiency of the optimization. In the first case, BB-BC optimization was compared with a GA in terms of the objective function of cost reduction. In the second case, the frame designs compared BB-BC optimization with simulated annealing regarding cost and CO_2 emissions reduction objective functions. The results showed that BB-BC optimization performed more efficiently in both cases than GA and simulated annealing. In the first case, BB-BC optimization decreased cost by 5.2% compared to GA design. In the second case, BB-BC optimization, a similar frame with US standard reinforcement, could meet the ACI standards. In both cases, BB-BC optimization reduced 5.7% cost of the equivalent frame. As a result, CO_2 emissions can be decreased for relatively low construction cost growth. In another study, a sustainable design method for RC members based on a discrete optimization method to reduce construction embodied emissions and costs was proposed by (Zhang and Zhang, 2021). The study used a multi-objective GA from "cradle to site" instead of using a single-objective one at just the material production phase. The optimization was followed by the numerical examination of a case study to compare the Pareto optimal solutions for RC beams. The results showed that a 5–6% additional construction cost could make up for a 14.7% emission reduction.

Lanikova et al. (2014) applied a probabilistic optimization method called reliability-based structure optimization to optimize the design of structures considering environmental and economic aspects (embodied energy (EE) related to concrete production, CO_2 emission, and cost). Monte Carlo, customized by the Latin hypercube sampling, was applied to evaluate the designed structure reliability. Two pole case studies of reinforced fiber concrete and prestressed spun concrete were used to demonstrate the method's applicability. The results showed that the quality and characteristics of the products should be considered in the design stage. Using the optimization method, 8.9% of cost and 11.1% of emissions were reduced compared to conventional design processes. Gan et al. (2019) applied an optimality criteria GA to introduce a new optimization method for high-rise RC, which is low carbon and cost-effective, first, by developing the optimum structural typology through crossover and mutation in GA, then, by single-member size optimization via the optimality criteria. The algorithm was continually employed to generate new designs until the optimal solution was determined. With this technique, the carbon emissions and cost of materials decreased by 18–24%. The framework can be used for other building types, such as steel structures. Mergos (2018) established an optimization platform to design an earthquake-resistant RC frame with minimum CO_2 emissions and cost. The author performed a mixed-integer GA with MATLAB for a three-floor building with two bay RC frame based on Eurocode 8 ductility groups for different peak ground accelerations, concrete classes, and embodied CO_2 scenarios for materials. Overall, thirty sorts of RC frame designs were assessed to select the optimum designs by running ten separate GAs for every RC design. Seismic designs with low ductility could produce more CO_2 emissions, up to 60%, compared to medium and high ductility designs. Moreover, peak ground accelerations design significantly enhanced the amount of CO_2 emissions, yet concrete classes less affected the amount of CO_2 emissions. Besides, for the low unit ratio value of the environmental impact of reinforcing steel to the respective impact of concrete, designs for the minimum costs generate more CO_2 emissions up to 13% than the designs for the minimum CO_2 emissions; however, the same unit ratio for medium and high value, the minimum CO_2 design solutions are nearly connected to the minimum cost design ones. Park et al. (2013) proposed an optimization model based on a GA for the optimum design of steel RC columns in tall buildings to diminish CO_2 emissions and cost

Table 2
Sustainable components design and production using ML techniques.

Authors	Sustainable Components	Soft Computing Method	Output
Lee et al. (2021)	Waffle slabs	NSGA-II algorithm	- Reduced CO_2 emissions and costs - Waffle forms specifications, particularly the ribs height and the distance between ribs, among the design parameters, had the highest impact on optimizing cost and CO_2 emissions - Regarding NSGA-II, the maximum generation was set to 40, and the crossover and mutation rates were 0.95 and 0.05, respectively
Zhang and Zhang (2021)	RC beams	Multi-objective genetic algorithm	- The results showed that a 6% additional construction cost could make up for a 14.7% emission reduction
Lanikova et al. (2014)	Structure design	Reliability-based structure optimization	- 8.9% of the cost and 11.1% of emissions were reduced in comparison to conventional design processes
Gan et al. (2019)	High-rise RC structure	Optimality criteria genetic algorithm	- CO_2 emissions and cost of materials decreased by 18–24%
Park et al. (2013)	Steel RC columns	Genetic algorithm-based optimization	- The proposed optimized design could decrease 30.3% of CO_2 emissions, 31.5% of the cost, and 7.8% of steel section and total concrete weights

in the construction stage. To consider both CO_2 emissions and cost, the overall CO_2 emissions amount was transformed to equal cost based on the concept of certified emissions reductions. Then the total cost was minimized using the optimization model, in parallel, meeting the constraints, including stress and constructability. The results showed that although the CO_2 emission and cost unit of materials with high strength are higher than the conventional materials, using high-strength steel and concrete (more concrete than steel) was required to obtain an optimum design. The proposed optimized design could decrease 30% CO_2 emissions, 31% cost, 7.8% steel section, and total concrete weights. Table 2 summarizes some of the sustainable components design and production using ML techniques.

4.1.1.3. Hybridized ML techniques in sustainable materials and components design/production. Classical optimization algorithms offer better estimation results than numerical and statistical methods; however, hybridized ML techniques address several issues of standalone ML algorithms. Golafshani et al. (2020) applied ANN and ANFIS techniques hybridized by Grey Wolf Optimizer to boost the function of the predictive models of CS for ordinary and high-performance concrete, including blast furnace slag and FA. The authors stated that meta-heuristic optimization algorithms used in the training stage of ANN and ANFIS methods decreased the weakness of classical optimization and resulted in more reliable outputs. Liu et al. (2021b) used ANN hybridized with swarm intelligence algorithms to predict carbonation depth for recycled aggregate concrete. The standalone machine learning models and hybrid ones were developed to compare the performance of the models. All the ANN models hybridized with swarm intelligence algorithms showed better performance than the standalone ANN model, particularly for the hybridized ANN model with a whale optimization algorithm. Moreover, hybrid methods were applied (Ashrafian et al., 2020; Moghaddas et al., 2022b) to prevent the local minima and boost the function of standalone optimization algorithms (Cook et al., 2019; Moghaddas et al., 2022a). A recent research (Golafshani et al., 2020) shows that applying the swarm intelligence algorithm to optimize the parameter of the ANN method can improve its generalization ability for predicting the mechanical performance of conventional concrete.

Other studies have also investigated hybridized ML techniques. García et al. (2020) introduced a hybrid particle swarm optimization method based upon db-scan clustering, which is an effective technique in binary combinatorial issues dealing with the design of reinforced earth retaining wall targeting to make a trade-off between cost and CO_2 emissions. Db-scan was applied as a discretization means. Thirty-two parameters (including geometric, geotechnical, safety, and ambient exposure factors) were involved in the wall design. The algorithm was employed to select low-cost and low-carbon designs. It was then compared with a random operator and K-means method. The results showed that the proposed optimization algorithm performs better quality of solutions and performance. When comparing db-scan with K-means, it gained significantly smaller dispersions. When comparing db-scan with an efficient algorithm adapted from the harmony search, db-scan achieved better results. Marti et al. (2016) applied a heuristic optimization algorithm combination of simulated annealing and mutation operator to find the best solution in a road bridge u-beam precast/prestressed concrete based on EE and cost, taking into account concrete type, geometry, slab, and beam reinforcement and prestressing steel. The results showed parabolic relation between span length and minimum energy. The estimated energy savings were calculated at around 24%. The optimum solution reached less span length in the cross direction and decreased the thickness and reinforcement of the slab. The study showed that cost and energy reduction did not have any contradiction. One Euro decrease in cost could save energy up to 4 kWh. Faridmehr et al. (2021a) applied an optimized artificial neural network combined with metaheuristic Bat optimization method to produce sustainable self-compacting geopolymer concrete, containing 50% of FA in the GBFS-FA with suitable strength as well as environmental impact mitigation. Zhang et al. (2020b) used a hybrid AI model based on a random forest–modified beetle antennae search algorithm to make oil palm shell concrete. The model had high prediction accuracy with a correlation coefficient of 0.96 on the test set. Along with appropriate CS, the oil palm shell concrete led to CO_2 reduction, natural resources conservation, and cost-efficiency. Golafshani et al. (2021) applied the combination of two types of machine learning algorithms. Type-1 and type-2 fuzzy inference systems were used to predict the CS of recycled aggregate concrete in a dataset containing 1868 data samples. The results showed higher accuracy and reliability than other standalone machine learning techniques. Martinez-Martin et al. (2012) provided a procedure for designing bridge RC piers to reach the optimized solutions based on the objective functions of cost, CO_2 emissions, and the congestion of reinforcing steel. A hybrid simulated annealing algorithm was applied considering the independent variable of materials, steel reinforcement usage, and dimensions. Three simulated annealing-based multi-objective algorithms based on the GAs mutation operator named MOSAMO1 to 3 were applied. The solutions assessment met the structural concrete Spanish Code. The optimization procedure was employed for a 23.97 m bridge pier. This case study contained 110 variables. Results revealed that the MOSAMO2 algorithm performed better than others considering the Pareto fronts definition. CO_2 and cost relationship were shown almost significant. The correlation between congestion of the bars with either cost or CO_2 was very inferior. In another study, Baandrup et al. (2020) introduced computational morphogenesis processes as a design concept to save weight in the girder design of long suspension bridges while maintaining manufacturability targeting reducing CO_2 emissions. Density-based topology optimization technique SIMP (Solid Isotropic Material with Penalization) based on gradient-based optimization algorithms was applied. The optimization aimed to enhance the model's stiffness in the center section while using a certain volume of materials. The method was applied to a bridge case

Table 3
Sustainable materials and components design/production using hybrid ML techniques.

Authors	Sustainable Materials/ Components	Soft Computing Method	Outputs
Sojobi and Liew (2022)	Bioinspired sandwich carbon-fiber reinforced polymer	Hybridized Taguchi method–response surface methodology–multiple objective optimization	- Substitution for steel in the recycled concrete beam led to CO_2 emissions reduction - Lightweight; 0.7 to 4.4 times better than RC structures in terms of fracture toughness, cost-effectiveness - Suitable for semi-automated systems and 3D printing
Faridmehr, Nehdi, Huseien, et al. (2021a)	Sustainable self-compacting geopolymer concrete	Optimized artificial neural network combined with metaheuristic bat optimization method	- Applying 50% of FA in the ground blast furnace slag (GBFS)-FA composition in self-compacting geopolymer concrete obtained suitable strength as well as environmental impact mitigation
Faridmehr, Nehdi, Nikoo, et al. (2021b)	Industrial byproduct-based alkali-activated mortars	Optimized hybrid model of principal component analysis – optimized artificial neural network –combined with the cuckoo optimization algorithm	- Mixtures with high content of FA had the least EE and CO_2 emissions - Mixtures with high content of POFA and GBFS had the most rate of EE and CO_2 emissions - All the above had less EE and CO_2 emissions than OPC-based mortar - Estimating EE and CO_2 emissions with R^2 values of 0.97 and 0.98, respectively
Zhang et al. (2021)	Silica fume concrete	Hybrid beetle antennae search algorithm– back propagation neural network	- Trade-off between embodied emissions and financial costs. An extra 6% cost could make up for a 14.7% emission reduction - The ML model had a high correlation coefficient (R-value of 0.96) and a low RMSE (value of 6.95 MPa) on the test set
García et al. (2020)	Reinforced earth retaining wall design (buttressed wall)	Hybrid particle swarm optimization based upon db-scan clustering	- Low-cost and low-carbon designs - The proposed optimization algorithm performed better quality of solutions and performance compared with the random operator and K-means method
Ahn et al. (2013)	RC frames	Integrated big bang and big crunch optimization	- Reduction in the total cost or the CO_2 emissions - By the optimization, 5.7% cost was reduced compared with the equivalent frame
Marti et al. (2016)	Road bridge u-beam precast/ prestressed concrete	Heuristic optimization algorithm combination of simulated annealing and mutation operator	- Concrete type, geometry, slab and beam reinforcement, and prestressing steel were input parameters - 24% energy saving was calculated
Mergos (2018)	Earthquake-resistant RC frame	Mixed-integer genetic algorithm	- Low ductility could produce more CO_2 emissions by up to 60% compared with medium and high ductility design - Designs for the minimum costs generated more CO_2 emissions by up to 13% than the designs for the minimum CO_2 emissions
Baandrup et al. (2020)	Girder design of long suspension bridges	Density-based topology optimization technique based on gradient-based optimization algorithms	- The results showed that 28.4% material weight saving, equal to 19,000 m^3 of concrete and 13,000 tonnes of steel, equal to 43,000 tonnes of CO_2 emissions reduction, was obtained
Martinez-Martin et al. (2012)	Bridge RC piers	Hybrid simulated annealing-based multi-objective algorithms based on the genetic algorithms	- CO_2 and cost relationship were shown to be almost practical - The correlation between congestion of the bars with either cost or CO_2 was inferior

Table 4
ML techniques for CO_2 emission reduction of on-site vehicles and equipment.

Reference	ML Technique	Equipment Type	Activities
Masih-Tehrani et al. (2020)	Genetic algorithm-based optimization	Tracked bulldozer	Three different terrains and particular digging depth
Masih-tehrani and Ebrahimi-nejad (2018)	Integer linear programming and genetic algorithm	Caterpillar D6T bulldozer	Different digging programs
Jassim et al. (2019)	Artificial neural network integrated with perception multilayer network (backward propagation learning method based on the Levenberg–Marquardt algorithm)	Caterpillar wheel loader	Material hauling
Choi et al. (2018)	Colony optimization algorithm	Ready-mixed concrete vehicle	Travel scheduling
Jassim et al. (2017)	Artificial neural network	Excavator	Material hauling
Trani et al. (2016)	Cluster analysis and linear regression	Earthwork vehicles of loaders, compactors, and excavators	Earthwork activities
Lewis et al. (2015)	Multiple linear regression	Wheel loaders, motor graders, and backhoes	Highway maintenance project: material hauling, excavating, fine and light grading
Hajji (2015)	Multiple linear regression	Excavator, bulldozer, and dump truck	Earthwork
Ahn and Lee (2013)	Discrete-event simulation	Excavator	Earth-moving activities and excavation
Abolhasani and Frey (2013)	Linear regression	Dozers, excavators, front-end loaders, off-highway trucks	Excavating and digging the earth, moving dirt from one location to another, etc.
Lewis et al. (2012)	Regression	Highway construction equipment	Idle and non-idle time of on-site construction operations
Boriboonsomsin et al. (2011)	Regression	Trucks	Traffic speed

study in Turkey. The results showed that the reduction of 28.4% of material weight savings, 19,000 m^3 of concrete, and 13,000 tonnes of steel equals 43,000 tonnes of CO_2 emissions. Table 3 summarizes some of the sustainable materials and components design/production using hybrid ML techniques.

4.1.2. On-site vehicles and equipment

On-site vehicles and equipment such as excavators, bulldozers and trucks for construction expose significant environmental impacts, which have been less addressed in research studies in comparison to the environmental impact of the building during the use phase, design, or even demolition and recycling stages (Sandanayake et al., 2017; Chena et al., 2017). Masih-Tehrani et al. (2020) developed a genetic-based optimization model to decrease the fuel usage and emissions of heavy-duty construction vehicles. A tracked bulldozer was modeled as the case study. The fuel usage and emissions maps were calculated using ADVISOR's data and the scaling process. The dry sandy soil was determined as the vehicle's working site on three different terrains, and a particular digging depth was defined for the optimization problem. The design variables considered were transmission gear number, engine speed, and throttle position. The trade-off between objective functions of fuel usage and engine emissions was addressed. By increasing the digging depth, the throttle position enhances. The range of 1,800 to 2, 400 rpm for engine speed is optimum, and the third gear is the optimum for fuel usage and emissions compared to other gears. In another study, Masih-tehrani and Ebrahimi-nejad (2018) proposed an optimization model based on the integration of integer linear programming and GA to solve the fuel rate and engine emissions elements problems in Caterpillar D6T bulldozer used in construction. The results proved that emissions and fuel rate performed better, with more than 31% in five case studies, when digging less than the maximum digging depth of the vehicle's blade. Emissions and fuel consumption showed improvement in emissions and fuel consumption up to 17.7% with the same digging time and up to 31.6% without the digging time limit in case of replacing the vehicle's manual transmission with a continuously variable transmission. Peng et al. (2016) employed a modular portable emissions measurement system of SEMTECH-DS, and a particle sampler to capture carbon-contained emissions and particulate matter pollutants in eleven different on-site equipment, including loaders, bulldozers, and excavators. The results revealed that CO emission factor was higher when the machinery was in idle status than when is operating. In construction vehicles, in comparison to road machinery, the CO emission was much more significant than NOx emission. The papers which have addressed the reduction of CO_2 emissions by reaching optimization models for on-site vehicles and equipment are summarized in Table 4.

4.1.3. Energy and life cycle assessment

Several studies addressed carrying out LCA on different concrete compositions (Thilakarathna et al., 2020; Alabduljabbar et al., 2020; Naseri et al., 2020). The mixture designs were predicted with varying techniques of ML. In (Thilakarathna et al., 2020), different supervised ML techniques of ANN, Gaussian process regression, SVM, decision trees, and linear regression were applied to predict the CS. ANN achieved the most accurate prediction function. LCA for different phases of raw material extraction, transport, and materials manufacturing (production stage) was conducted on more than 70,0000 concrete compositions created by differing input parameters. The benchmark function was provided successfully to evaluate the appropriate limit for embodied carbon and ML algorithms to produce concrete compositions with lower embodied carbon and the defined specific CS. In another study, Naseri et al. (2020) examined 232 different concrete mixture collected from previously published literature seeking for the most sustainable mixture considering other criteria of cost, CS and environmental effects (such as energy, resource usage and CO_2 emission) using meta-heuristic-based ML technique. Then the most sustainable composition was compared to a conventional concrete composition through LCA to indicate its long-term advantages for sustainability. Alabduljabbar et al. (2020) conducted LCA on various concrete compositions, of which mechanical characteristics were calculated using optimized ANN. The compositions reduced the cost of the alkali-activated aggregate composition by 41.2% in comparison to the natural aggregate ones. The CO_2 emissions were below the 85% fuel production gained using natural aggregates. Mao et al. (2019) introduced a regression model to predict the CO_2 emission of a building during its life cycle regarding designing parameters. Four methods of principal component analysis, multi-layer perceptron, SVM, and RF were then employed to initiate regression models. Finally, process analysis and comparisons of the developed model were carried out. SVM proved to have the best function for accurate prediction, with having 0.8 coefficient of determination among the four methods. Table 5 shows the ML techniques combined with LCA to mitigate CO_2 emissions in construction.

Table 5
ML techniques combined with LCA to mitigate CO_2 emissions.

Reference	ML Techniques	Activity
Thilakarathna et al. (2020)	Artificial neural network, Gaussian process regression, support vector machine, decision trees, and linear regression	Minimizing the embodied carbon of different high-strength concrete and ultra-high-strength concrete compositions while predicting the CS and proportion of the mixes
Naseri et al. (2020)	Meta-heuristic-based ML	Looking for the most sustainable concrete mixture considering different criteria of cost, CS, and environmental effects (such as energy, resource usage, and CO_2 emission) out of 232 concrete mixtures
Alabduljabbar et al. (2020)	Artificial neural network	Conducting LCA on the various concrete compositions, of which mechanical characteristics were calculated
Mao et al. (2019)	Principal component analysis, multi-layer perceptron, support vector machine, and random forest	Predicting the CO_2 emissions of a building during its life cycle regarding 12 determining designing parameters
Olanrewaju (2021)	Integration of three methods of index decomposition analysis, artificial neural network, and data envelopment analysis	Introducing an integrated model for energy savings leading to GHG emissions reduction for the construction industry from 1994 to 2016
Mergos (2018)	Genetic Algorithm	Establishing an optimization platform to design an earthquake-resistant RC frame with minimum CO_2 emissions and cost. A cradle to gate LCA in the stages of raw material extraction and factory manufacturing was considered
Ferreiro-Cabello et al. (2018)	Meta-model based on deep learning	Predicting the best solutions for T-shaped one-way slab design considering deflection, rigidity, cost, CO_2 emissions, and EE
Fellaou et al. (2018)	Multiple linear regressions	Optimizing the combustion in cement kiln precalciners and reducing CO_2 emissions by decreasing the unburned rate by analyzing historical and experimental design data
Shen and Lepech (2017)	Stochastic life cycle impact assessment and lifecycle optimization	Proposing a platform for reducing the environmental impact of the preservation of RC transportation infrastructure by applying stochastic life cycle impact assessment and lifecycle optimization
Gardezi et al. (2016)	Multivariate regression	Developing a novel tool to predict CO_2 integrating LCA, building information modeling (BIM), and ML technique

4.1.4. Optimized decision-making and solution-based platforms

Rapid, automatic, and optimized decision-making platforms can highly contribute to CO_2 emission reduction in construction. Some research studies have focused on developing solution-based platforms using AI and ML techniques (Huynh et al., 2021; Li et al., 2017a; Koo and Park, 2012).

NoParast et al. (2021) developed an integrated single-product, multi-stage and multi-objective model of a sustainable closed-loop supply chain to optimize the concrete supply chain. Customers, manufacturing factories, suppliers, and recycling areas were taken as the network components of the concrete industry. In addition, other parameters included transportation costs, transportation options, customers' demand, sorts of expenses, each category's distances, centers' capacity limits, divided products' unit limits, GHG emissions in the duration of the supply chain, and generated wastes were considered. A mixed-integer linear and multi-objective model of genetic algorithm (NSGAIII) was selected to assess and optimize the function of the supply chain in a closed loop consisting of a four-level network. The results from the Pareto solution revealed that increasing the usage of recycled aggregates can decrease the quarries' excavation in concrete production. Besides, in the case of green cement usage in the concrete supply chain, the main parameter that determines the amount of GHG emissions is the transportation distance from the source of the green cement. In the case of inward recycling unit provision, GHG emissions decreased by 14%, while the demand for virgin aggregates was enhanced by 16%, and the cost was boosted by 24% compared to the outward recycling plant system. Li et al. (2017b) also introduced a genetic-based optimization platform to assess and decrease the CO_2 emissions generated from construction labor allocation in cold winters. First, the construction activities and processes were simulated by applying discrete event simulation using Simphony.NET to measure and analyze the generated CO_2 emissions for each construction activity and on-site heating in winter. Then, the labor-intensive laborer size for construction activities (such as framing, siding, drywall boarding, drywall taping, stage1 finishing, and painting) was optimized with a GA-based on CO_2 emissions. A case study was used for the applicability and validation of this platform. This hybrid simulation and optimization platform could decrease CO_2 emissions by 21.7% in winter by selecting a different activity start date and optimizing labor allocation. In another study, Huynh et al. (2021) developed a multiple objective social group optimization, which is stated to be a new evolutionary optimization method containing different stages of starting, improving, interacting and ending to optimize four factors of time, quality, and cost in the construction industry CO_2 emission. Two case studies were applied to validate the method solutions. Besides, evidence-based reasoning was used to choose the best solution for the project operation. The results showed that the proposed optimization model surpassed the four popular NSGA-II, MOABC, MOPSO, and MODE algorithms in terms of effectiveness and efficiency and illustrated convergence and diversity, vaster spread, and more excellent uniformity of the solutions. Yazdani et al. (2021) presented a new method to optimize the production scheduling and due dates for off-site prefabricated construction projects to find high-quality alternatives. As production issues have a stochastic nature dealing with complexity and uncertainty, a meta-heuristic framework containing three integrated simulation-optimization algorithms of GA, differential evolution, and an imperialist competitive algorithm was applied. The test showed that the differential evolution method performs better than other methods. Moreover, differential evolution still acted robustly regarding the behavior of the developed methods in indifferent problem size levels. The suggested algorithm yielded the highest values of diversification measurement of 26.11 and 40.27; the highest values of hyper-volume of 0.88 and 0.89 in the first and the second cases, respectively. The suggested algorithm found solutions with the lowest mean ideal distance and spread values of 0.88 and 0.45 in the case 1 and of 0.75 and 0.69 in case 2.

Li and Gao (2018) implemented an optimized algorithm of integrated particle swarm optimization and back propagation neural network to predict the CO_2 emission peak in the cement industry in China from 2016 to 2050. Carbon emissions were calculated and compared under various scenarios. Then, the technology integrated with the most effective CO_2 reduction impact was suggested. The outcomes showed that only China's strategies for CO_2 reduction in the cement industry are plans execution related to capacity reduction and second generation of new technology systems of dry cement technology. In this regard, before 2030, carbon emissions reached peak CO_2 emissions. The authors suggested 2,482 million tons of carbon emission control in the cement industry by 2030. These predictions provided sources for the government for further decision-making. Zhang and Wang (2017) assessed the uncertainty of building construction embodied emissions in the phases of material manufacturing, transportation, and construction job-site tasks. A stochastic analysis based on data quality indicators, a partly quantitative procedure to determine the original data quality, was conducted. A 17-storey building was selected as a case study for the comparison of deterministic emissions with stochastic ones. Standard deviation of 248.9 tCO_2e of the whole emissions was achieved for the uncertainty of input factors and the sample mean of 5,891.97 tCO_2e, consistent with the deterministic outcomes. Meanwhile, scenario analyses, encompassing system boundary, possible decrease in material usage and emissions, usage of local production and low energy consumption was performed to measure the uncertainty of the scenario. The results illustrated that application of only primary materials led to 5–10% of embodied emissions underestimation. scenarios containing local production of concrete, steel, and masonry led to a significant decrease in emissions. Proper data duration and transformation coefficients are necessary for model uncertainty reduction. Koo and Park (2012) established an optimization model based on a GA to find the best transfer route in the process of construction materials delivery to minimize fuel consumption and CO_2 emission. The factors of road type, truck type, and fuel efficiency were considered, and the constraints contained truck numbers, capacity, trip length, and overall delivery load. A case study of a real construction was conducted to validate the model. Finally, the GA and the simulated-annealing model were compared to prove the model's feasibility. The results showed that the genetic-based model performs better than simulated annealing regarding fuel usage in similar weight of materials delivery. All these optimization platforms help automated and more accurate decision-making in reducing CO_2 emissions in different construction parts.

4.1.5. Real-world monitoring

Real-world data acquisition and monitoring were investigated by several scholars (Van Tonder and Low, 2021; Liu et al., 2020) for the reduction of CO_2 emissions by installing sensors and applying IoT. Tao et al. (2018) reported offering a GHG emission monitoring platform based upon IoT to monitor emissions of prefabricated manufacturing in near real-time. Radio Frequency Identification (RFID) sensors were used for the manufactured component identification. Wu et al. (2014) developed a platform for real-time measurement and data transfer model of the energy usage and CO_2 emissions key factors like building materials quantity, transportation, electricity, and fuel consumption in the complete building life cycle using RFID system.

Karimi et al. (2021a) developed a model for the proper duty cycle of wheel loaders in construction in order to reduce heavy diesel machinery fuel consumption and emissions. They collected 80,000 data on wheel loader digging activity by placing a global positioning system (GPS). A GA model was carried out to choose the best composition of micro-trips. The results showed that the emitted carbon monoxide was lower than Environmental Protection Agency (EPA). But, in terms of fuel, Tehran wheel loader duty cycle consumes 265% more than European NRTC and 86.12% greater than EPA. Liu et al. (2020) presented a sensor-based real-time system for recording and visualizing emissions in prefabricated construction sites for three on-site equipment: construction elevators, tower cranes, and transfer vehicles. This cyber-physical system included four physical, sensing, computing, and interaction layers. To monitor the operational condition of the tower crane, acceleration sensors were applied. The working condition of construction elevators was monitored with barometric sensors. GPS sensors were used for the travel time records of transfer vehicles and to record and transfer the operating hours of these vehicles to a remote server through a connection like Wi-Fi or GPRS (General Packet Radio Service) module. A database was responsible for storing the data of numbers, quantities, machine power, unit energy consumption, and emission parameters. Machines' carbon emission was estimated at the computing level based on data computing and LCA. At the interaction level, the carbon emission data could be sent to and visualized in an application on a smartphone or laptop. To effectively address the 3D visualizations, a BIM model of the site was used to show GHG emission data. Addressing on-site real-time monitoring for off-road machinery and measuring machinery run time which leads to optimization of the construction task schedules, are among the novelties of this study. The authors suggested strengthening the visualization of emissions data, bilateral interaction between virtual and physical environments, and further debugging and more comprehensive system optimization for future studies.

4.2. Discussion, gaps, and future research directions

The content analyses showed that five main conceptual themes could be derived from the related literature. Almost 60% of the articles were related to sustainable materials and components design/production, mainly focusing on reducing CO_2 in cement and concrete mixture production, such as (Long et al., 2021) and (Wimala et al., 2019). The second category investigated the on-site vehicles and equipment (Masih-tehrani and Ebrahimi-nejad, 2018) and (Peng et al., 2016). Energy and life cycle assessment (Thilakarathna et al., 2020; Alabduljabbar et al., 2020), optimization, decision-making, and solution-based platforms (NoParast et al., 2021; Li et al., 2017b), and real-world monitoring (Wu et al., 2014; Liu et al., 2020) were the other categories. Lu et al. (2020) reviewed studies on carbon emissions in the green building construction sector. In the existing literature, they reached five main themes of building carbon emissions reduction prospects, properties of materials, performance measurement, management practice, and decarbonizing design, model, and strategies.

This paper reviewed the existing literature for CO_2 emission initiatives in construction using ML techniques. In this section, as the results of the content review, limitations, gaps, and a set of key directions for future research investigations are presented for each cluster as follows:

1- There are several directions for future research studies that can be addressed. For sustainable concrete development, investigating the quality depreciation and materials loss in the recycling process by considering a broader range of input variables (e.g., cement type, curing conditions, and aggregate types and grading) is recommended to increase the generalization ability of the proposed model (NoParast et al., 2021; Zhang et al., 2021). Furthermore, more intelligent models need to be developed to design or predict different concrete mixtures (Teixeira et al., 2021; Zhang et al., 2021) with different types and volumes of supplementary materials such as fly ash, slag, silica fume, manufactured sand, coarse mineral aggregate, and fibers, recycled aggregates (Teixeira et al., 2021), different cement raw materials (Ates et al., 2021), binder (Shubbar et al., 2018), etc. that minimize materials (Van Tonder and Low, 2021), construction and environmental costs (Gan et al., 2019), reduce CO_2 emissions, and maximize favorable mechanical properties.

More accurate data is needed for training and testing the multi-objective optimization model (Zhang et al., 2021). This ensures more refined tuning of hyperparameters and further improves the ability of the model to obtain meaningful patterns from data with noise. In addition, improving the mathematical model by modifying the model scenario and employing other solution methods for multi-objective optimization (NoParast et al., 2021), applying more improved and new prediction models capable of predicting the CS of OPC (Ates et al., 2021), introducing advanced data pre-processing techniques such as missing data imputation and semi-supervised learning to replace the input and output missing values in the database (Zhang et al., 2020b) are suggested for future research. Furthermore, upgrading optimization algorithms and extending the proposed algorithms to solve reliability optimization (Huynh et al., 2021; Zhang et al., 2020b) of trade-off time, cost, quality, labor, and carbon dioxide emission factors in generalized construction projects (Zhang et al., 2020a) are other future directions.

2- In the context of on-site vehicles and equipment, most studies have investigated the CO_2 emissions of a few on-site vehicles, like wheel loaders, bulldozers, and excavators. The study effort should be expanded to include the other equipment types (Karimi et al., 2021a) in real-world data sets, including off-road trucks and track loaders. In most studies, the driving cycle of these vehicles are synthetic rather than examining real-world driving patterns (Karimi et al., 2021a). One limitation of these research studies could be the assumption that vehicles operate in a steady state and with the same performance efficiency throughout excavation operations. Another limitation could be that using basic data extracted from the manufacturer's handbook for the excavators to generate the input data of the proposed models ignores the effects of uncertain conditions, such as a long idle time when the excavator has to move to a new location (Jassim et al., 2017). Also, output data for energy and CO_2 emission depend on indirect measurement. It is strongly recommended that the calculation of emission inventory should be based on massive real-world emission results (Peng et al., 2016; Choi et al., 2018). More emission tests on construction equipment are thus required. Future studies will focus on operational-level emission modeling of on-site earthmoving equipment (Jassim et al., 2019), such as hydraulic excavators, wheel loaders, bulldozers, etc. (Barati and Shen, 2016; Lewis et al., 2015). It will also be required to investigate the effect of driving behavior on the emission rates of construction equipment and the best strategies for emission reduction at operational level (Barati and Shen, 2016).

Future data collection should include information regarding the vehicle task and components of the duty cycle, such as lateral movement of the vehicle and usage of vehicle accessories and attachments, such as blades and buckets. Furthermore, data regarding the extent of the vehicle task, such as the volume of dirt excavated, could be the basis for the development of production activity-specific emission factors (e.g., the mass of pollutant emitted per cubic yard of material excavated). Field studies should be designed and conducted for a variety of purposes, such as characterization of emission factors and inventories, comparison of vehicle technologies, and evaluation of operational strategies for performing a given task, among others (Abolhasani and Frey, 2013). Combining the real-world driving cycle of on-site vehicles with incorporating other parameters, such as construction site soil type, digging program, and digging load (Masih-Tehrani et al., 2020), can provide valuable information on the working activity of these vehicles and can help the process being optimized regarding fuel usage and emissions. Regarding excavators, using different values of performance efficiencies for excavator fleets to cover all real-life operational scenarios employed in earth-moving operations can be further investigated. In addition, the study of other parameters that highly affect the behavior under different conditions of earth density and bucket payload, such as engine torque (Masih-Tehrani et al., 2020), to compare the prediction efficiency of the proposed model in the case of using engine load factor or engine torque is recommended.

Regarding fuel energy consumption during earthworks (Jassim et al., 2019), in-depth methodology developments are needed, through the involvement of earthmoving machine producers and their users, particularly earthworks sub-contractors. The comparison between predicted and real data in several case studies could strongly validate the method. Some machinery producers have specific fuel counters installed on their latest equipment models. However, for other significant earthwork types, such as civil construction, a future in-depth analysis considering different consumption agents and materials would be required to fit the predictive method (Trani et al., 2016). Furthermore, for estimating fuel use and carbon dioxide emissions, it is recommended for future research to validate and calibrate the presented models by real-world fuel use and CO_2 emissions data collected from construction equipment. This will be done by using a portable emissions measurement system that is able to record second-by-second fuel use, emissions and engine data from the equipment performing earthwork activities (Hajji, 2015).

Carbon emission rates for vehicle non-idle and idle modes were determined by using some representative data rather than equipment-specific data, as data are limited on the fuel use and emission rates that can be linked to different operation modes of a variety of construction equipment. Additional research is required to build a database of fuel use and emission rates that can be expandable to commonly used construction equipment with various engine sizes, model years, and service hours (Ahn and Lee, 2013). Future research endeavors will focus on examining factors that affect the idle rate of equipment through further investigation of equipment usage patterns related to the operating equipment efficiency found in various types of construction operations. Further research will also involve developing a feasible monitoring system for the operational efficiency of construction equipment in use.

3- Regarding LCA, developing life cycle cost in addition to an eco-friendly optimal design model and integrating the two to produce more efficient solutions to mitigate the environmental impact of the construction of structural elements like long-span waffle slabs (Lee et al., 2021) are essential for CO_2 emissions reduction. Enrichment of data sources to accomplish a thorough LCA is essential (D'Amico et al., 2019; Mao et al., 2019). Thus, future research should include the integration and implementation of a database with energy (cooling and electricity demand), environmental (considering all phases of an LCA), economic (costs and return time) and social aspects. It should provide a comprehensive building sustainability assessment (D'Amico et al., 2019). It is suggested to consider the trade-off between potential life cycle impact and structural capacity when conducting maintenance and specifying a maintenance regime (Shen and Lepech, 2017).

4- In the construction sector, assembly technology should be used to optimize the production structure while also focusing on research and development (Yang et al., 2021). Additionally, off-site operations should reduce energy consumption and provide clean energy for building material production. Several behavioral, technical, infrastructure, market and legal barriers can be overcome by establishing centers of excellence for prefabrication construction, effective regulatory guidelines, and standards for prefabricated construction. Architects, engineers, and built-environment professionals are required to be re-trained in design building technology (NoParast et al., 2021). This training can help minimize construction and demolition waste generation at the end of the useful life of prefabricated and traditional concrete structures, extend the useful life of building components, avert waste disposal of recyclable construction wastes in landfills (Alaneme and Mbadike, 2021), and extend the service life of landfills. Semi-automated systems are recommended for prefabricated and modular construction to harness the benefits of 3D printing (NoParast et al., 2021). Some policy suggestions should be addressed, such as encouraging building energy conservation, improving the energy efficiency of the construction industry, adjusting the use of building materials, and improving the extant policies for building emission reduction (Peng, 2019).

Upgrading the optimization algorithms (Zhang et al., 2020a) and proposing frameworks that allow adapting the parameters based on the algorithm's results would generate even more robust methods than the current ones. In addition, real-time data in some construction tasks, e.g., scheduling, is recommended for future research (Yazdani et al., 2021).

5- The number of studies for real-time data capturing in construction targeting CO_2 emission reduction is insufficient, mostly on a small or laboratory scale. Real large-scale research studies are recommended. Strengthening the proposed system in terms of the visual presentation of GHG emission data and two-way interaction between the physical and virtual worlds requires additional optimization and debugging work before these systems can be used at a broader scale (Liu et al., 2020). The application scope of real-world monitoring should be expanded to the entire construction phase. Emission activities, including components manufacturing, components transportation, on-site installation, and construction waste transportation, should be monitored in future studies together in one real project. Meanwhile, additional GHG emission sources, such as fuel consumption, water consumption, and construction auxiliary material usage, should be considered. More advanced technology also is needed to be considered. For instance, a one-way laser sensor should be used instead of a dual one to avoid the risk of laser light deviation (Tao et al., 2018). In addition, a reliable communication network should be built to transmit emission data over an extended distance.

5. Conclusions

The present review implemented a systematic review and content analysis led to identifying five main sub-topics that have been investigated in the construction ML-based CO_2 emission reduction literature: 1) sustainable materials and components design/production, 2) on-site vehicles and equipment, 3) energy and life cycle assessment, 4) optimization, decision-making and solution-based platforms, and 5) real-world monitoring.

The paper applied a mixed method of bibliographic analysis and content review to identify different directions in construction to use ML for CO_2 emissions reduction in the current literature. It provided a detailed content review of five clusters, the gaps and future research directions. The gaps and future research can be valuable for scholars in further investigations. Various AI and ML techniques, such as artificial neural networks, genetic algorithms, regression models, support vector machines, and decision trees, were used to predict and optimize CO_2 emissions in different construction parts. These tools help in more automatic and accurate prediction and optimization of sustainable construction to reduce CO_2 emissions.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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Appendix

Table A
Journals publishing the relevant articles based on the search result.

Journal	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	Total	%
Cleaner Production	0	0	0	0	0	0	0	0	0	1	0	1	0	5	2	9	11.53
Construction and Building Materials	0	0	0	0	0	0	0	0	0	1	1	1	1	0	4	8	10.25
Automation in Construction	0	0	0	0	0	0	0	0	0	1	0	1	0	2	0	4	5.12
Construction Engineering and Management	0	0	0	0	0	1	2	0	0	0	0	1	0	0	0	4	5.12
Energy and Buildings	0	0	0	0	0	0	0	0	0	0	2	1	1	0	0	4	5.12
Materials	0	0	0	0	0	0	0	0	0	0	0	0	2	1	1	4	5.12
Transportation Research Record	0	0	0	0	1	1	0	0	1	0	0	0	0	0	0	3	3.84
Building Engineering	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	2	2.56
Energy	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	2	2.56
International Journal of Civil Engineering	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	2	2.56
International Journal of Sustainable Engineering	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	2	2.56
Sustainability (Switzerland)	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	2	2.56
Sustainability	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	2	2.56
Advanced Engineering Informatics	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	1.28
Advances in Structural Engineering	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	1.28
Aerosol and Air Quality Research	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	1.28
Air and Waste Management Association	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	1.28
Building and Environment	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1.28
Case Studies in Construction Materials	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1.28
Composite Structures	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1.28
Energies	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	1.28
Engineering, Design and Technology	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1.28
Engineering Structures	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	1.28
Environmental Engineering (United States)	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	1.28
Environmental Science and Pollution Research	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1.28

(*continued on next page*)

Table A (*continued*)

Journal	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	Total	%
Geotechnical and Geological Engineering	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	1.28
Geotechnical Testing Journal	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	1.28
Habitat International	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	1.28
Infrastructure Systems	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	1.28
Environmental Management	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	1.28
International Journal of Engineering, Transactions B: Applications	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	1.28
International Journal of Sustainable Construction Engineering and Technology	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	1.28
Journal of Zhejiang University: Science A	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	1.28
Materials-Design and Applications	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1.28
Mathematics	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	1.28
Nanomaterials		0	0													1	1.28
Nature Communications	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	1.28
Resources, Conservation and Recycling	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1.28
SAE International Journal of Commercial Vehicles	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1.28
Sensors (Switzerland)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1.28
Soils and Foundations	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	1.28
South African Journal of Industrial Engineering	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1.28
Sustainable Production and Consumption	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1.28

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