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A Systematic Literature Review on Integrating Machine Learning Algorithms and Metaheuristic Algorithms in Optimizing Sustainable Digital Architectural Design

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Abstract This systematic literature review investigates how machine learning (ML) algorithms and metaheuristic methods have been integrated into sustainable digital architectural design optimization over the past two decades. The study analyzes 42 peer-reviewed publications, highlighting the critical role of these technologies in enhancing energy efficiency, structural optimization, and environmental sustainability. This review showcases the growing use of ML and metaheuristics to reshape traditional architectural practices by addressing multi-objective optimization models such as generative design and performance improvement. Furthermore, the review outlines the approaches taken in the study, focusing on algorithmic decision-making for material and energy consumption optimization. Despite the promising advancements, several limitations are outlined, including non-standardized procedures and limited applications in practice. The research calls for mixed-method procedures and empirical studies for the validation of algorithmic models in real architectural projects. Practical implications of this study include the potential for ML and metaheuristic algorithms to enhance design procedures, reduce environmental impact, and achieve higher energy conservation, which will result in more sustainable building solutions. Social implications are the broader use of such technologies with the aim to achieve sustainability goals within urban environments, make resource allocation more effective, and enhance occupant comfort. This review contributes to the literature by pointing out the need for standard methods and introducing these technologies into practice to have the maximum impact on sustainable design.

Keywords Machine Learning, Metaheuristic Algorithms, Sustainable Architecture, Energy Optimization, Generative Design

1. Introduction

New technologies, specifically the combination of artificial intelligence (AI) and optimization algorithms, have been propelling the rapid speed of architectural design [1]. Traditional architecture does little to contribute to the resolution of the complex problems of sustainability and efficiency in urban cities. Architectures and urban planners are eager for new means of incorporating sustainability into their design for issues like climate change, dwindling resources, and human-centric space [2]. Merging Machine Learning (ML) algorithms with metaheuristic optimization techniques is seen as the most promising way of bettering the decision-making process and the architectural design to be energy-efficient, use improved materials, and perform better overall [3]. On the other hand, while there is enormous potential for effects, comprehensive integration of such technologies in architectural design is fragmentary, and the level of systematic assessments considering their application and impact has been comparatively limited to date [4], [5]. This review, therefore, seeks to address this shortfall by critically assessing where ML crosses over with metaheuristic algorithms in optimizing green digital architectural designs.

Recent past has seen a broader application of digital technologies in the architecture, engineering, and construction (AEC) industry. It has transformed traditional practices by leveraging Building Information Modeling (BIM), AI-enabled software, and parametric design tools that enable architects and engineers to create dynamic, responsive, and optimized designs [6]. ML algorithms have a vital part to play in predictive modeling, performance analysis, as well as design optimization [7]. They can predict energy consumption, simulate environmental factors, and optimize shape and material of buildings to meet defined sustainability objectives using large datasets [8]. This is also facilitated by the implementations of metaheuristic algorithms like Genetic Algorithms (GA), Particle Swarm Optimization (PSO), and Ant Colony Optimization (ACO) that have established optimization infrastructures searching optimal solutions of the design within constraints [9].

While this is highly promising, at the integration level, several challenges and limitations are associated with such technologies. Such algorithmic models are usually so complex that architects and designers need domain-specific competence and technical skills in computational methods [10]. Most importantly, compatibility among these digital tools and software platform interoperability are significant barriers [11]. However, the advances in computational architecture hint at a trend where smooth integrations of ML and optimization algorithms within architectural workflows have emerged [12].

Research has also established that combining ML algorithms and metaheuristic approaches improves design outcomes. For instance, generative design AI tools support fast exploration of multiple alternatives to optimize daylight access, energy efficiency, and structural integrity [13]. The studies have also shown that ML models combined with optimization techniques can make scenario-based predictions about building performance, thus leading to more resilient and sustainable architectural solutions. These technologies also contribute to the development of smart urban environments through optimization in resource allocation, enhancement in the energy performances of buildings, and improved quality of life for occupants.

Even with these developments, the synergistic use of ML and metaheuristic algorithms in sustainable digital architecture has yet to be comprehended fully. Most works either explore solo usages or highlight case studies, but an overview of the potentials and limitations of the benefits involved remains lacking. Besides, non-standard methodologies and metrics for evaluation in the literature make comparing the effectiveness of different algorithms and their applicability to architectural design hard.

This study aims to critically examine the integration of Artificial Intelligence (AI) applications, specifically Machine Learning (ML) algorithms and metaheuristic techniques, in optimizing sustainable digital architectural design. It seeks to uncover how these advanced technologies enhance energy efficiency, material optimization, and the overall sustainability of architectural practices.

This systematic literature review focuses on key AI applications, including algorithm-driven design (ADD), generative design systems, smart city planning, and sustainable construction techniques. By emphasizing AI's transformative potential, the study aims to provide professionals, academics, and policy analysts in architecture and urban planning with a comprehensive understanding of the methodologies adopted. It also identifies areas most in need of further research and development to fill gaps between theory advancement and use.

The research question that guides this review is: How and what do Machine Learning and Metaheuristic Algorithms bring about in the practice of digital architectural design in terms of sustainability, efficiency, and human-centered development, and what are the implications of these for the future practice of architecture?

This question encapsulates the objective of the study to investigate the collective influence of ML and metaheuristic algorithms in creating optimized, sustainable, functional, and aesthetically driven designs while impacting future directions and trends in architectural practices.

2. Research Methodology

The review offers a systematic approach to a critical literature review of Artificial Intelligence (AI) integration into optimization algorithms for environmentally friendly digital architectural design. A systematic and organized review is required because such a process reduces the chances of biased outcomes, thereby allowing for analysis devoid of preconceived notions or expectations. The given study's methodology will involve scoping research, formulating research questions, establishing the selection criteria for identified studies, details of the precise search strategy, assessment of the quality of the included studies, and systematic extraction and analysis of data from those sources.

Following the criteria mentioned, the first part of this review provides a comprehensive exploration of the topic and its contextual background. Indeed, this lays the ground for an in-depth assessment of the subject matter. The sections that follow discuss the different facets of the review methodology. They include establishing the criteria for study selection, describing the systematic process in which the literature related to the review question was collected, detailing the standards for assessing the quality of the studies and defining the methods utilized for data extraction and synthesis. By adopting a duly structured methodological approach, this paper will try to present an all-inclusive, non-partisan integration of existing knowledge on how AI and optimization algorithms can contribute to sustainable architectural and urban design.

2.1. Search Strategy and Databases Used

The search strategy is comprehensive; it therefore encompasses automated and manual approaches to comprehensively investigate the influence of artificial intelligence (AI) on architectural and urban design. The computerized approach entails a thorough electronic search using keywords relevant to the research objectives. As recommended in the approach by Kitchenham et al. [14], the first step for an automated search is identifying primary studies. The manual search of sources complements this to find more relevant materials, making the related literature review comprehensive and inclusive.

The present study is based on several prestigious databases like Scopus, ISI Web of Science, and SpringerLink. These sources include some of the most well-known online collections of renowned articles related to engineering, architectural design, and structural analysis. Databases like ScienceDirect and ISI Web of Science provide access to thousands of scientific and technical papers. By contrast, SpringerLink stands out as a famous international scientific publisher, providing valuable sources for scholars. These include books and journals related to architectural and urban design.

The catchwords are individually and in combinations linked by Boolean operators such as "AND" OR "to refine the search. Keywords used in this study range across a broad spectrum, from the very specific to the more general: "Artificial Intelligence in design-meaning the application of AI technologies in architectural and urban planning processes." The architectural design process denotes the systematic approach architects use in conceptualizing and realizing building designs, which are increasingly enhanced through AI technologies. Concerning "urban planning," AI has been noted to improve the efficiency and sustainability of existing practices in urban development. The concept of "sustainable development" in the design of architecture and town planning places an ecologically sensitive and resource-efficient environment in focus that, to a great degree, AI technologies have been used to reinforce so far. "Smart cities" are urban areas that use AI and other technological innovations to improve living conditions and urban management. Generative design in AI describes algorithmic procedures that produce manifold design solutions according to predefined input parameters.

These core keywords are combined with other terms to extend the search: "data-driven urban design," "AI in sustainable architecture," "machine learning in design," "AI in spatial planning," and "technological innovations in urban development." This seeks to construct a complete research framework that captures the interplay between AI, architecture, and urban planning in a structured way to have an efficient and comprehensive literature search process, as outlined by Kitchenham et al. [14].

Given the stated research focus, steps for conducting an in-depth search are schematized below in Table 1, which prescribes five phases of investigation regarding integrating machine learning with metaheuristics algorithms for optimization in sustainable digital architectural design. Phase I focuses on the contribution of algorithms, such as machine learning and metaheuristic techniques, to enhance the architectural design process and urban planning regarding efficiency and sustainability considerations. The contents of this first phase provide the necessary background for the subsequent phases to understand how these technologies are used in practice.

Further phases deal with different dimensions of sustainable design and innovation. The second phase emphasizes algorithms applied to achieve sustainability goals in architectural practice and intelligent city development. The third phase focuses on algorithm-driven generative design and data-driven optimization, which underlines these technologies' innovative potential for architectural and urban solutions. The fourth phase involved the technological and methodological developments regarding algorithmic tools and their revolutionary impact on traditional design methodologies. The final phase deals with the ethical and social consequences of those algorithms' use, ensuring the review does not merely stay at the technological level but also extends to general social and environmental impacts. Such a planned approach permits detailed awareness of how machine learning is integrated with metaheuristic algorithms in sustainable architectural design.

A multi-stage search strategy was utilized to search for relevant literature on the integration of machine learning and metaheuristic algorithms for the best sustainable digital architectural design. This was supplemented by an automated search followed by a manual search with forward and backward search strategies, commonly known as "snowballing" by Watson and Webster [15]. The procedure entailed the hand-screening of references and citations to the critical literature, an advisable procedure for the assurance of full coverage of the relevant researches, including perhaps those that can be missed when using automated search. The retroactive search permits systematic source discovery. The forward search was explicitly used to track influence and development in cited studies, providing confirmation and, in some cases, an extension of the findings in the referenced research.

Mendeley was used to organize and manage the collected studies, ensuring that the references were handled effectively and duplicate records were removed.

The research systematically followed the review protocols outlined by Kitchenham et al. [14], which encompass the preparation, execution, and documentation phases of the review process. This methodology was divided into several sub-steps: formulating the review question, defining the research methodology, establishing inclusion and exclusion criteria, performing a quality assessment, and synthesizing evidence to address the research question comprehensively. Watson and Webster [15] emphasized that integrating forward and backward searches with automated search techniques provides a more holistic and thorough approach to literature review by ensuring an in-depth exploration of relevant content. Furthermore, recent research has underscored the critical role of machine learning in digital architecture and sustainable design, demonstrating its effectiveness in optimizing energy consumption, enhancing environmental performance, and improving the efficiency of architectural solutions [16]. This highlights the growing convergence of artificial intelligence and architectural practices, reinforcing the need for further empirical validation and methodological advancements in the field.

After preliminary validation, duplicate records were removed to ensure their accuracy and relevancy. Abstracts of the studies were screened for inclusion based on the defined inclusion criteria. A full review of methodology and finding documentation was performed for the relevant studies, with particular attention given to how each applied algorithm to optimize sustainable digital architecture. Open coding supported an inductive content analysis, fully synthesizing and interpreting the data. The process for selecting articles as part of this systematic literature review is presented in Figure 1 through a flow diagram. The first phase involved a general search in different databases: 1,084 articles came from Springer, 692 from Scopus, and 230 from the ISI Web of Science. Thus, duplicate records among those databases were found and excluded in the second stage, reducing the dataset by 27 articles.

The third step involved the verification of the abstracts of the remaining 1,057 articles. It was done by applying predefined inclusion criteria. The application of this procedure excluded 812 records and retained 245 for possible further consideration. Fourth, the authors read the introduction, methodological section, and discussion of the remaining articles with great detail to confirm that the article's contents adhere to the study's inclusion criteria. Of these, 89 further articles were excluded due to irrelevance or a lack of alignment with the study focus. In addition, another 24 articles from the full-text assessment were excluded; thus, after such refinement, 42 articles met all the inclusion criteria and were assessed as appropriate for final analysis in this systematic review.

Table 1. Framework for Developing a Comprehensive Search Strategy

Number	Phase Title	Phase Description
1	Algorithm Integration in Sustainable Architecture	• Applications of Machine Learning in Architectural Design: Discussing how machine learning algorithms are employed to enhance digital architectural design for efficiency and sustainability. • Metaheuristic Algorithms in Urban Planning: Investigating the use of metaheuristic algorithms in optimizing urban planning and architectural solutions for flexible and resilient cities.
2	Sustainability and Smart Architectural Optimization	• Sustainable Design via Algorithms: Examining the potential of machine learning and metaheuristic algorithms in assisting in achieving sustainability goals via computer-aided architectural design. • Algorithm-Driven Smart Cities: Investigating the effect of such algorithms for the optimization and development of smart cities, and more specifically to optimize the usage of resources, energy efficiency, and urban sustainability.
3	Innovation in Algorithmic Architectural Design	• Machine Learning and Metaheuristic Generative Design: Exploration of the capacity to employ machine learning and metaheuristic-inspired generative design for encouraging innovation and efficient architectural form. • Data-Driven Urban Design Optimization: Unveiling how big data and algorithmic thinking can be employed to guide decision-making in urban design and optimize architectural solutions to achieve sustainability.
4	Technological and Methodological Advances	• Algorithmic Design Tools and Techniques: Evaluating the scope of machine learning and metaheuristic techniques used in sustainable architectural design in an effort to achieve improved decision-making and performance outcomes. • TransFormation Design Methodologies: Investigating the way these types of algorithms re-molding traditional urban planning and building design approaches to bring about novel and more efficient sustainable solutions.
5	Ethical and Societal Impact of Algorithmic Design	• Algorithm Ethics and Machine Learning in Architecture: Investigating the ethics of employing such technologies to create sustainable urban design and architectural work. • Societal Impacts and Sustainability Outcomes: Evaluating the social and environmental performance effect of algorithmic planning, for example, on quality of life, urban resilience, and building people-oriented, sustainable cities.

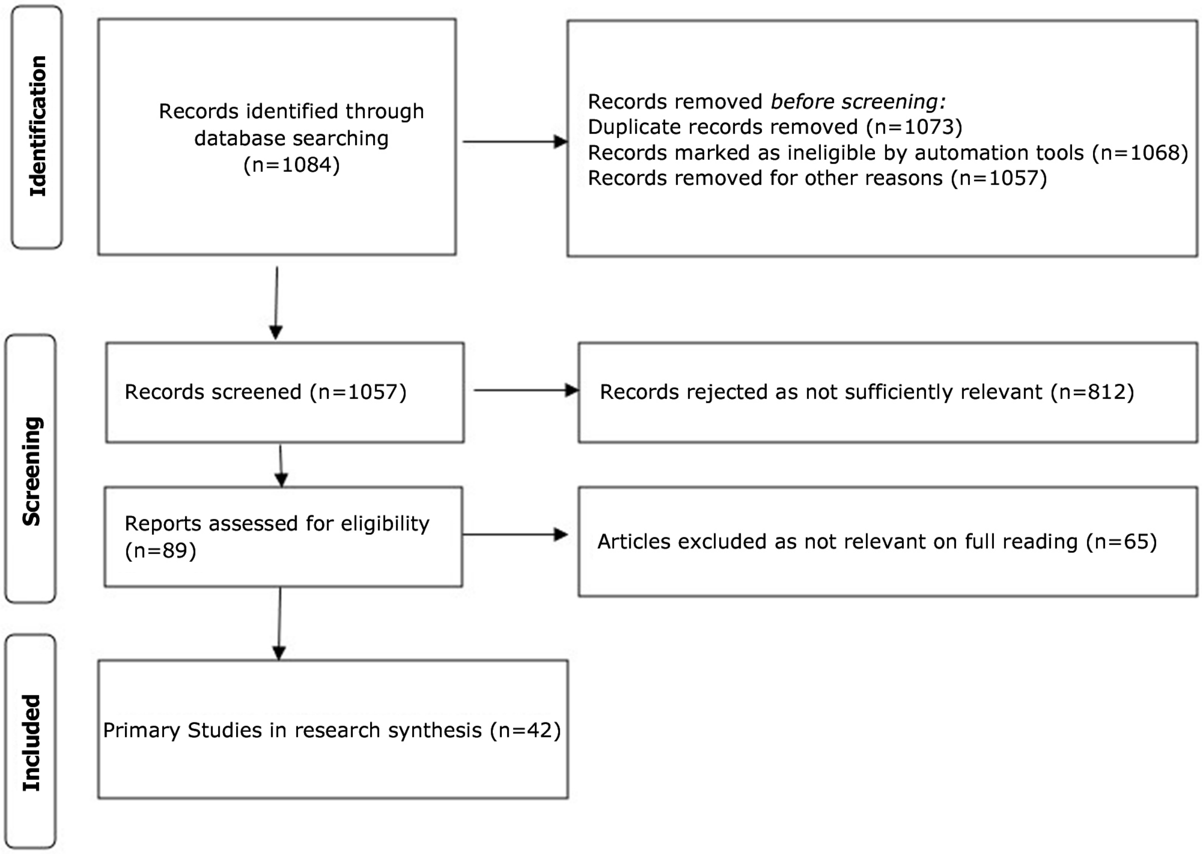

Figure 1. PRISMA Flow chart for SLR included searches of databases and registers only (Source: By researchers)

2.2. Inclusion and Exclusion Criteria

Only empirical and theoretical studies published in peer-reviewed journals between 2003 and 2023 were considered. These studies investigate the use of ML and metaheuristic algorithms in architectural design, urban planning, or innovative city development, as shown in recent works such as Chegari et al. [17] and Ramya et al. [18]. The selected studies employ valid and reliable methodologies, often involving human participants such as architects, urban planners, and related professionals. For example, metaheuristic techniques for optimizing daylighting and energy efficiency have been highlighted in Bekdaş and Nigdeli [19] and Olanrewaju and Bruno [20].

Only papers written in English were analyzed to ensure homogeneity. Papers that were non-empirical, employed unreliable methods, or were of no applicability to the use of ML and metaheuristic algorithm integration in architecture or urban application were not included. Those that were applied elsewhere other than in architecture and urban design or only in computer simulations but not in application, for instance, Hazra et al. [21], were not included. Also excluded were non-English publications for ease of access and consistency. The inclusion and exclusion criteria gave a clear-cut and well-defined reviewing process, as stated by Veisi et al. [22]. The criteria were applied consistently so as to give little bias and reliability. Data extraction form attached in Appendix A systematically normalized data from the 42 studies included, such as study ID, title, authors, year of publication, outcome, methodology, geographic locations, and sample size. This allowed for critical review and unbiased judgment of the studies. Upon review, 42 primary studies were determined to be relevant to the field of the study and to be of high quality of publication.

2.3. Study Quality Assessment (QA)

Table 2 indicates the Quality Assessment Criteria (QAC) for assessing the strength and applicability of studies to be used in the systematic literature review on integrating metaheuristic algorithms and machine learning in sustainable architectural design. The criteria contain five significant points that will ensure the studies meet the required standards for this area of research.

QAC1: The review checks whether the study incorporates machine learning and metaheuristic algorithms into architectural design, their application, and their various effects. QAC2: This checks if the research justifies how such algorithms ensure development towards sustainability and efficiency in design, which is the main objective of the systematic review. QAC3: Is there a well-defined relationship between the algorithms and sustainable architecture besides being articulated to ensure clarity and relevance?

QAC4 checks if the research clearly outlines the architectural or urban setting and how that setting reflects the study's purpose to ensure the research applies directly. Finally, QAC5 examines the methodology documentation, the results' transparency and credibility, and whether the studies will provide clear and dependable evidence. These criteria permit standardization and comprehensiveness of the literature review; they align selected studies to their objectives.

Figure 2 depicts the outcome of the paper selection process from three primary databases, Springer, Scopus, and ISI Web of Knowledge. The chart contains two types of data: one is "Initial Results," and another one is "Relevant Studies." The "Initial Results" bars are colored orange and represent the overall number of papers searched from each database in the first stage of the search process. Consequently, Scopus had the highest preliminary results with 692 studies, followed by ISI Web of Knowledge with 230, and Springer with 162. Finally, the "Relevant Studies" bars, colored in a darker tone, reflect how many studies were considered relevant after using the study's criteria for inclusion. Again, Scopus contributed the most with 23 relevant studies, followed by ISI Web of Knowledge with 13 and Springer with 6.

This figure illustrates how dramatically the number of studies decreases as a selection process narrows the search to those relevant to the systematic literature review. The severe screening and filtering ensure that only high-quality, relevant studies will be selected for the final analysis.

Table 2. Study Quality Assessment Criteria (QAC)

Criteria No.	Quality criteria
QAC1	Does the study explore integrating machine learning and metaheuristic algorithms in architectural design?
QAC2	Does the research address how these algorithms enhance sustainability and optimize design efficiency?
QAC3	Is the relationship between machine learning algorithms, metaheuristic approaches, and sustainable architecture clearly defined?
QAC4	Is the specific architectural or urban planning context accurately specified and relevant to the study's objectives?
QAC5	Is the research methodology well-documented, and are the results presented clearly and reliably?

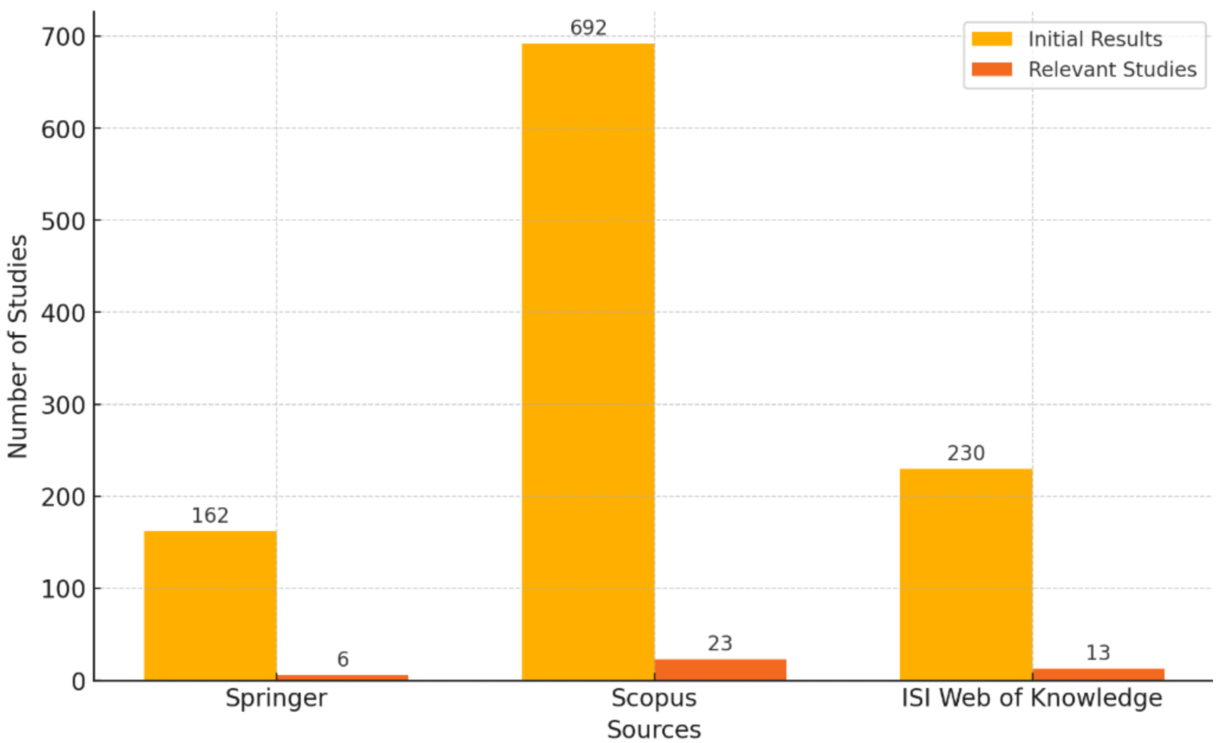

Figure 2. The results from the paper selection procedure

3. Results

Figure 3 illustrates the chronological distribution of critical references for integrating machine learning into metaheuristics when applied to digital architectural design, sustainability, and environmental performance. It can be seen that the number of research works has grown considerably in the last few years. In 2019, few studies showed interest in just one publication, which gradually increased to two in 2020. Further, the number of studies grew to 13 in the year 2021, which is considered the watermark year for studies in this area. The decline has decreased by one to 11 publications in 2022. On a general trend, the graph is upward, with 2023 having the highest number of studies (15). This growth demonstrates that, in recent years, the research area has taken giant steps and begun to acquire a lot of importance; the role played by machine learning and metaheuristic algorithms is becoming solid as critical allies to developing increasingly sustainable architecture.

Figure 4 presents the nature of the research methodologies used in the reviewed studies. The results show that most reviewed studies (31) adopt a quantitative approach, as data-driven analysis and quantifiable outcomes are critical for evaluating algorithm performance and optimization capabilities within architecture applications. This firm reliance on quantitative methodologies aligns with the parametric approach to eco-design, where measurable parameters such as energy efficiency, material optimization, and structural performance are central to achieving sustainable outcomes.

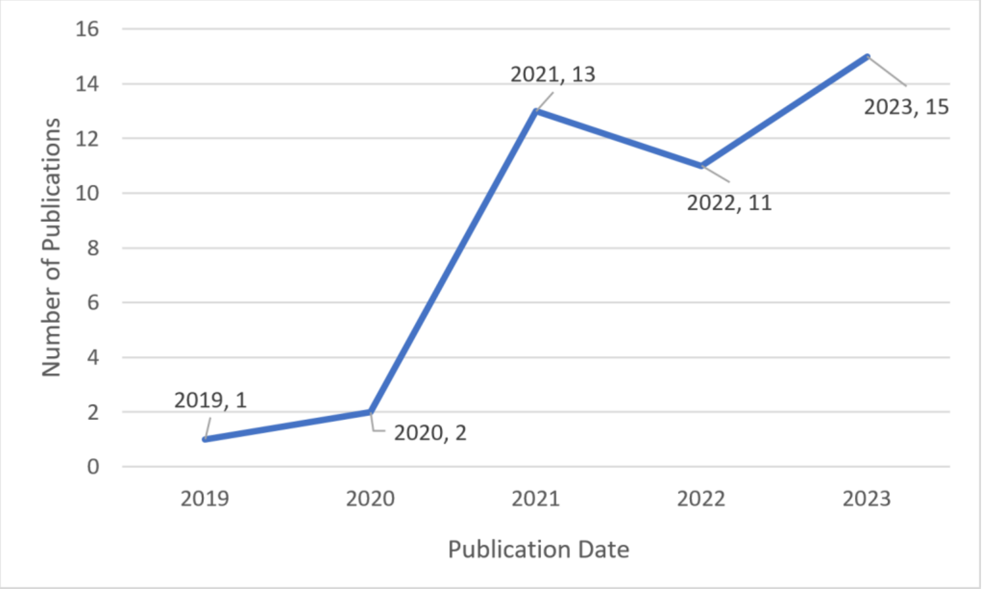

Figure 3. Chronological distribution of the critical studies

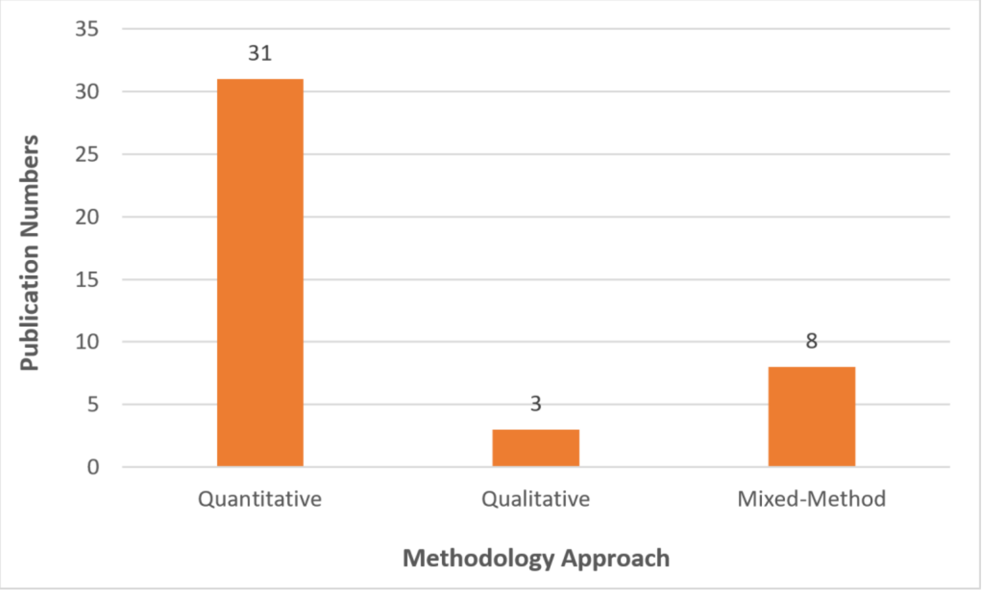

Figure 4. An analysis of the types of research methodologies employed

The figure also indicates a limited number of qualitative studies (3), highlighting an opportunity to delve deeper into contextual insights, such as stakeholder perspectives and the ethical implications of integrating machine learning and metaheuristic algorithms in sustainable design. Secondly, only eight studies adopted a mixed-method approach, signaling a gap and an opportunity for future research to combine quantitative rigor with qualitative insights. Mixed-method approaches can provide a more comprehensive understanding of the measurable performance metrics and their contextual application in real-world architectural and urban planning scenarios, thus addressing the broader goals of sustainable design.

3.1. Application and Performance of Machine Learning and Metaheuristic Algorithms in Architectural and Construction Design

The findings have indicated the different applications and potentials that machine learning (ML) and metaheuristic algorithms can possess in construction and architectural design optimization. These studies demonstrated how these modern algorithms help in improving structural efficiency, predictive modeling, and resource utilization in city and architecture planning.

Talbi [23] conducted a comprehensive review of integration of metaheuristics with machine learning to categorize different methods and applications in architectural and engineering optimization. Ekici et al. [24] implemented AI-based optimizational methods on skyscrapers and required application of metaheuristic solutions in green city architecture.

Yet another research, e.g., Seyyedabbasi [25], suggested reinforcement learning-metaheuristic algorithms for solving global optimization issues in architectural design and construction. This study emphasizes the importance of adaptive optimization models in the evolving field of intelligent urban planning. Likewise, Kazeem et al. [26] examined AI and ML application in sustainable construction and introduced a framework for the application of metaheuristics in modern architectural practice.

For instance, Joshi et al. [27] applied a hybrid metaheuristic model to forecast the compressive strength of concrete via a deep learning-based approach and proved the capability of deep neural networks in optimizing materials. A study by Alkabbani et al. [28] presented machine learning and metaheuristic methods for renewable power prediction, which impacted energy-efficient building design directly.

Other contributions were on sustainability, such as the work of Ahmed and Darwish [29], who developed a metaheuristic-enhanced automatic CNN architecture design approach for optimizing building structures. Additionally, Alkhazaleh et al. [30] focused on energy-efficient building design using fuzzy-based models synthesized with metaheuristic algorithms to improve the accuracy of thermal energy demand predictions.

On the other hand, Saha et al. [31] contributed to sensor-based smart architecture by applying metaheuristic and machine learning methods in IoT data fusion for building automation and efficiency. Similarly, Chou and Truong [32] developed a multi-step energy forecasting model by integrating time-series analysis with metaheuristic-optimized machine learning, offering an advanced smart city energy management framework.

In summary, the papers reviewed here have indicated the great potential of integrating ML and metaheuristic algorithms into architectural design for improved sustainability, structural efficiency, and resource management. Therefore, these papers clearly show how algorithmic solutions can support modern construction practices in creating optimized, sustainable, and innovative architectural solutions.

3.2. Optimization of Energy Performance and Environmental Sustainability

The thematic area in this section falls within the application of machine learning (ML) and metaheuristic algorithms to architectural and urban systems to enhance energy efficiency and sustainability. Studies in this thematic area have highlighted many ways advanced algorithms can be leveraged to optimize energy use, enhance building design, and imbue the architectonics process with sustainability to further responsible environmental and energy-efficient solutions.

For instance, Zhang and Pei [33] applied hybrid machine learning techniques integrated with metaheuristic algorithms for cooling load forecasting in buildings. Their study emphasized how predictive AI-driven models enhance energy efficiency while maintaining indoor comfort, contributing significantly to sustainable building design. Kumar et al. [34] extended these ideas by proposing an AI-powered fusion transformer and recurrent neural network architecture for energy-efficient electric vehicle charging in smart urban environments.

Ekici et al. [35] also contributed by developing an artificial intelligence-driven multi-zone optimization (MUZO) approach to enhance daylight and energy efficiency in high-rise buildings during the early design phase. Their results proved that integrating artificial intelligence (AI) in the conceptual design phase enhances final building designs' energy performance. Another recent study by Peng [36] introduced a machine learning-based approach to predict residential cooling loads by examining six metaheuristic optimization algorithms.

Bian et al. [37] discussed how metaheuristic-based machine learning algorithms optimize power consumption in HVAC systems. Their work illustrates how AI-driven models refine energy demand management, enhancing the sustainability of urban structures. Similarly, Bouabdallaoui et al. [38] combined artificial neural networks with the PSO algorithm to forecast wind energy production and emphasized the success of ML-based models in enhancing the accuracy of energy prediction.

Some other notable works are Wang et al. [39], which formulated an end-to-end multi-target scheduling framework for sustainable operation in smart cities via deep reinforcement learning. They shed light on the fact that the use of metaheuristic algorithms increases operation effectiveness in flexible job scheduling. Furthermore, Ming [40] analyzed hybrid machine learning models incorporated with metaheuristic algorithms in the prediction of cooling loads to indicate how computational intelligence supports energy-saving HVAC options.

Another significant contribution is Wu [41], who described a green communication system using AI for smart hospital operations, such that resources would be properly managed and operations optimized. This cross-disciplinary work shows how metaheuristic and machine learning approaches could be applied to sustainable architecture and urban infrastructure.

The findings show that Building Information Modeling (BIM) integrates AI-based approaches, such as machine learning and metaheuristic algorithms, in a seamless manner to optimize parameters like energy efficiency and material utilization. For instance, BIM supports real-time simulation and predictive modeling, which allows architects to analyze different design options and achieve optimum sustainability performance. The empirical data from research falling under this thematic area establishes the fact that ML and metaheuristic algorithms offer more interfacing with architecture and urban planning to improve energy performance and environmental sustainability for buildings and cities. Through the use of these new technologies, planners and architects can create more efficient, sustainable, and resilient urban systems and buildings, thus creating a greener and more energy-efficient built environment.

3.3. Exploration of Methodological Diversity and Gaps in Research

Table 3 analyzes those studies contributing to methodological diversity and gaps in machine learning (ML) and metaheuristic algorithms in sustainable architecture and construction. The theme of this paper is highly significant because it highlights how distinct research approaches contribute to advancing sustainable digital architectural design. Furthermore, the integration of ML and metaheuristics represents computational methodologies at the forefront of scientific innovation.

The trend shown in Table 3 indicates that most of the listed studies are qualitative, often reviewing and exploring how AI technologies affect architecture, energy management, and urban planning. For instance, studies by Sulaiman and Mustaffa [42] and Feng [43] examine AI applications, emphasizing sustainable development and integrating technology into building energy management. While these studies provide essential theoretical insights, they also reveal a lack of empirical implementation regarding these technologies in real-world scenarios.

Certain mixed-method studies, such as Ali and Rakshit [44], illustrate how quantitative measures of performance may be integrated with qualitative results in an integrated analysis of applications based on AI and metaheuristics. This is highly relevant to the subject explored in this paper, in which the application of machine learning and metaheuristics to sustainable digital architectural design optimization is involved. These hybrid approaches adhere to the objective of blending technical data, i.e., performance data and computational performance, with qualitative data like user experience and design flexibility to develop an integrated framework for sustainable architectural practice.

The findings of this thematic analysis are fed directly back into this research by way of identifying the need for mixed research approaches when exploring ML and metaheuristic algorithm optimization in architectural design. While qualitative reviews play a critical role in establishing theoretical contexts and identifying technological trends, further empirical and mixed-method research that invokes quantitative analysis and qualitative confirmation remains urgently needed. These integrations allow for more insightful and serious assessments of AI applications that bridge the gap between theoretical advancement and actual application in sustainable architecture.

Table 3. Thematic Analysis - Exploration of Methodological Diversity and Gaps in Research

Citation	Major Findings	Study Contribution
[19]	Developed an intrusion detection system for intelligent environments using deep learning with metaheuristics, integrating quantitative and qualitative analyses.	Demonstrated the application of a mixed-method approach, combining algorithmic performance metrics with contextual insights into the practical applications of security systems in architecture.
[20]	Proposed a hybrid metaheuristic algorithm (T-APSSA) for building façade optimization, integrating simulation efficiency and design performance evaluation.	We utilized a mixed-method approach to bridge quantitative simulation results with qualitative design insights, addressing the practical application in architectural design.
[25]	Surveyed the integration of ML with metaheuristics, providing a detailed taxonomy and identifying research opportunities.	A qualitative review highlighting the diversity of methodologies and identifying gaps and future directions for integrating AI in architecture and urban planning.
[28]	Investigated the role of AI and ML in enhancing construction processes and sustainable communities, focusing on energy management and waste reduction.	Offered a qualitative overview of AI applications in construction, emphasizing the need for more comprehensive and integrated research methodologies to explore sustainability impacts.
[31]	Reviewed ML and metaheuristics in renewable energy forecasting, focusing on wind and solar power models.	Provided a qualitative analysis of existing models, pinpointing methodological gaps and suggesting areas for improving the integration of AI technologies in energy management systems.
[34]	Utilized machine learning and metaheuristics for IoT-based sensor data analysis, enhancing smart monitoring applications in diverse domains.	It adopted a mixed-method approach, combining quantitative data analysis with qualitative evaluations of IoT applications in architectural environments, highlighting its potential for broader research.
[37]	Reviewed cementitious material mixture optimization using ML and metaheuristics, proposing the Beetle Antenna Search algorithm for improved results.	Conducted a qualitative review, identifying methodological gaps in optimizing construction materials and proposing future research avenues for integrating AI techniques.
[44]	Explored AI, ML, and DL applications across the construction lifecycle, emphasizing the role of smart vision technologies.	A qualitative study provides a comprehensive review of AI technologies in construction, highlighting areas where more diverse methodologies could enrich understanding.
[46]	Reviewed intelligent controllers and optimization techniques for building energy management, emphasizing their alignment with sustainable development goals.	A qualitative review identifies gaps in the implementation of AI for building energy management and suggests improvements in methodological diversity for future studies.
[51]	Analyzed the application of 24 different multi-objective algorithms (MOAs) in structural optimization, showcasing their efficiency.	A qualitative exploration of the MOAs used in structural optimization, outlining the need for further integration of mixed-method approaches to assess the impact on real-world applications fully.
[55]	Explored the integration of AI, IoT, and big data in the Architecture, Engineering, and Construction (AEC) industry, highlighting challenges and future directions.	A qualitative review focusing on the methodological gaps in the application of AI and IoT technologies in AEC suggests a need for more mixed-method studies to bridge theory and practice.

4. Discussion

This review highlights the exemplary role played by Artificial Intelligence (AI), particularly Machine Learning (ML) and metaheuristic algorithms, in the optimization of sustainable architectural design. AI-driven methods have improved energy efficiency, resource allocation optimization, and enabled innovative architectural adaptability solutions. Such technological advancements have an immediate effect in solving the most important issues within the discipline, such as minimizing resource usage, environmental performance optimization, and streamlining sustainable building practices. The studies captured demonstrate that AI enables predictive modeling of energy use, allows for material efficiency through the application of generative design processes, and encourages structural integrity through the application of metaheuristic optimization algorithms. AI models allow for multi-objective optimization of sustainability, functionality, and aesthetics in building design.

In spite of these developments, there remain considerable challenges in standardization and practical application. Though theoretical development in AI-based architecture has been extensive, its scalability in real life is a crucial challenge. The literature emphasizes the need for developing standardized assessment metrics to evaluate the impact of AI on architectural sustainability efficiently. Overcoming these challenges will enable broader acceptance of AI and metaheuristics in practical applications, allowing these technologies to achieve their full potential in architectural innovation.

Thematic analysis revealed important contributions of metaheuristic algorithms and ML, namely to enhance structural performance and predictive modeling. Zhang and Pei [33] and Kumar et al. [34] are just some examples demonstrating how these technologies can enhance existing models for the prediction of structural behavior and the optimization of environmental parameters for green building. The findings follow the trend toward responsive and resilient building designs that evolve and react dynamically to changing environmental conditions.

In addition, the blending of genetic algorithms, deep reinforcement learning, and optimization techniques in environmental modeling—evident from the works of Ekici et al. [35] and Peng [36]—provides strength to the applications of these technologies in optimizing building performance at varied scales.

One of the predominant research themes includes applying metaheuristic methods in order to optimize complex architectural and urban planning challenges concerning energy efficiency, structural optimality, and resource optimality. Some of the high-order algorithms include Genetic Algorithms (GA), Particle Swarm Optimization (PSO), and Ant Colony Optimization (ACO) that have efficient mechanisms in place for minimizing or maximizing larger-scale design variables subject to differing constraints. Studies such as Bian et al. [37] and Bouabdallaoui et al. [38] set the effectiveness of such algorithms in optimizing interactions between such vital architectural factors as orientation, façade composition, and material qualities. Such intricate interactions are often challenging for conventional optimization tools to manage, and thus the importance of AI-based paradigms in green architecture. Incorporating data-driven metaheuristic models can potentially allow architects and engineers to develop adaptive, energy-conscious solutions enhancing long-term environmental responsibility.

The study also points out that energy optimization is a key issue in sustainable building planning. Studies like Wang et al. [39] and Ming [40] support this observation by showing how AI-based multi-objective optimization models contribute to environmental sustainability and energy efficiency. For instance, Wu [41] optimized energy-saving in smart hospital communication networks, where he highlighted the use of AI for operational efficiency and resource allocation. These researches are aligned with broader architectural trends that focus on sustainability from the initial stages of design, so that consideration of energy performance is integrated within the process of planning and development.

The increasing methodological diversity of AI-fueled architecture research suggests an improved understanding of the strengths of combining different methodologies. The majority of the research, such as Sulaiman and Mustaffa [42] and Feng [43], highlights the conjoining of quantitative analysis with qualitative results in filling the gap between theoretical development and practical application. The observation lends justification to the review's objective of evaluating AI-based models in real-world architectural contexts. Mixed-method approaches offer a holistic perspective on AI's contribution to architecture by integrating technical performance criteria with user experience and design flexibility components.

Despite the advancements seen in the results, there are still some limitations. Quantitative methods are prevalent in the literature, focusing on computational performance and efficiency metrics. Mixed-method and qualitative studies are not well represented. Future research must explore the social, cultural, and practical sides of AI and metaheuristic integration into actual architectural projects. As Ali and Rakshit [44] suggest, incorporating more qualitative studies will allow for the measurement of stakeholder attitudes toward AI-based architectural innovation, which will lead to more real-world applicability.

Besides, the review emphasizes the need for standardized evaluation models to provide comparability and consistency in AI and metaheuristic applications in architecture. The majority of current studies, e.g., Zhang and Pei [33], have a tendency to give general summaries of AI applications in construction without defining standardized performance measures. With such standards, there will be better measurement of algorithmic scalability and efficiency, enabling these technologies to be used extensively in architectural practices.

This review confirms that the integration of ML into metaheuristic algorithms holds revolutionary potential for sustainable architectural design. Enhancing methodological methods, enhancing practical implementation approaches, and applying standardized evaluation criteria are suggested for future research to enhance the application of AI in maximizing energy efficiency, structural performance, and sustainable architectural innovation.

4.1. Theoretical Implications

The findings from this systematic literature review highlight significant theoretical implications for incorporating machine learning (ML) and metaheuristic algorithms in sustainable digital architectural design. This study advances insights into how computational optimization techniques enhance architectural processes, reinforcing theoretical frameworks that integrate ML and metaheuristic algorithms for improving energy efficiency, sustainability, and adaptive design strategies.

One critical area where these methods have demonstrated substantial impact is energy performance optimization, particularly in predicting and managing cooling loads in architectural design. The study by Zhang and Pei [45] illustrates how hybrid ML models combined with metaheuristic algorithms optimize cooling load forecasting, showcasing the effectiveness of computational integration in enhancing energy efficiency and environmental sustainability. This supports the broader application of multi-objective optimization models in improving structural efficiency and material utilization.

Beyond identifying advancements, this review uncovers gaps in current theoretical frameworks. While numerous studies have examined the individual contributions of ML and metaheuristics in architecture, an integrated holistic theoretical model that fully incorporates these technologies across all architectural phases remains limited. Existing research primarily focuses on specific areas such as energy modeling or material optimization, but lacks a unified framework addressing how these technologies collectively optimize architectural processes. Kumar et al. [46] emphasize the importance of developing integrated computational frameworks that systematically apply ML and metaheuristics to various architectural design stages, particularly in predictive energy modeling and environmental sustainability applications.

Recent research has highlighted the interaction between AI-driven design methodologies and sustainable optimization strategies, demonstrating that reinforcement learning (RL) combined with metaheuristic algorithms enables dynamic architectural optimization, allowing real-time adjustments of design parameters based on environmental variables. Ekici et al. [47] demonstrate the application of multi-zone optimization techniques in high-rise building design, showcasing how AI-enhanced models optimize architectural configurations for sustainability and efficiency.

A growing trend in architectural theories involves automation, real-time optimization, and adaptive design paradigms. The integration of AI and metaheuristic algorithms with digital twin-based modeling has shown promise in enabling predictive analytics and simulation-driven architectural design. Peng [48] explores how machine learning-based cooling load predictions contribute to intelligent energy management, reinforcing the role of AI-driven sustainability solutions in modern architectural design practices. The increasing reliance on computational intelligence enables architects to develop smarter, more responsive, and environmentally sustainable structures.

4.2. Academic Implications

This review provides a critical academic perspective by analyzing methodologies and approaches that shape the practice of architectural design using machine learning (ML) and metaheuristic algorithms. Academically, the findings emphasize the necessity of integrating advanced computational methods into architectural and engineering education. With ML and metaheuristics continuously transforming architectural processes, students require computational proficiency to effectively apply these technologies in practice. Zhou et al. [49] highlight that incorporating AI-driven design methodologies into educational programs enhances students' ability to create effective, energy-efficient, and sustainable architectural solutions. Universities and research institutions expand their curricula by introducing specialized courses and modules focused on AI-based architectural design, computational optimization, and green architecture, ensuring that professionals develop the knowledge and expertise required by the evolving industry.

This review also identifies research gaps and provides a foundation for further academic inquiry. A notable gap exists in the application of mixed-method approaches within ML and metaheuristics research, indicating that architectural implementation remains underexplored. Masouleh [50] argues that empirical studies on ML-driven architectural optimization contribute to understanding the real-world applicability of such technologies. To address this, academic institutions facilitate interdisciplinary collaboration between AI researchers, architects, and sustainability experts, strengthening research that connects theoretical advancements with real-world applications. By promoting empirical studies and incorporating AI-driven optimization techniques into real projects, academia enhances the understanding of both the benefits and challenges of ML and metaheuristic algorithms in architectural design.

The integration of AI and optimization techniques in education extends beyond theoretical instruction to experiential learning. Oliva et al. [51] stress the importance of hands-on training in computational design, allowing students to develop problem-solving skills through direct engagement with ML-based and metaheuristic optimization models. This data-driven architectural education model fosters innovation and sustainability, ensuring that architects interpret and implement AI-based generative design solutions effectively in professional settings.

Despite the increasing adoption of AI in architectural education, challenges persist in standardizing AI applications in academic curricula. While AI and metaheuristic algorithms gain prominence in research, structured frameworks for assessing their educational impact remain insufficient. Shah et al. [52] argue that universities establish formal evaluation methodologies to measure the effectiveness of AI-based architectural training, ensuring that students acquire both theoretical knowledge and practical expertise. Establishing such assessment frameworks improves computational design education, enabling the integration of AI technologies into sustainable architectural practices.

4.3. Recommendations and Future Work

These findings from this review denote various areas where future studies could improve to better integrate machine learning (ML) and metaheuristic algorithms in sustainable architectural practice. The first is the need for more mixed-methods studies combining quantitative and qualitative approaches. By integrating these methodologies, future studies can validate the algorithmic models in practical, real-world architectural contexts, increasing the understanding of their potential efficacy and limitations. This will ultimately allow researchers to weigh data-driven insights against contextual evaluations to ensure that algorithms performing exceedingly well under controlled conditions translate effectively within actual constructions and designs. Strengthening research through diverse data sources would further enhance the generalizability of results and improve the robustness of architectural AI applications.

Real-world implementation should be emphasized more, particularly in testing these algorithms on live architectural projects. Future studies should prioritize applying these technologies at least in the conceptual and early design stages to evaluate their scalability, adaptability, and performance in real-world settings. This approach will help narrow the gap between theoretical development and practical application, ensuring that AI-driven optimization techniques are effective in simulations and applicable in actual design and construction processes.

Other recommendations include the creation of standardized frameworks to evaluate algorithm performance within architectural contexts. The current research landscape lacks consistency in methodologies and metrics, making meaningful comparisons challenging. Establishing standardized frameworks will facilitate benchmarking and help researchers identify the most effective methods for integrating these advanced technologies into practice. This should be complemented by an extension of qualitative and stakeholder-oriented research to align AI and metaheuristic solutions with industry needs. Architects, engineers, urban planners, and building occupants can provide valuable insights into these technologies' usability and real-world impact, ensuring they meet practical requirements and user expectations. Incorporating stakeholder feedback into the development process will pave the way for more user-oriented and adaptable architectural solutions, ultimately enhancing the effectiveness of technological integrations within the built environment.

Future research should focus on real-world implementation and validation of ML and metaheuristic models in sustainable architecture.

5. Conclusions

This systematic literature review concludes that integrating machine learning algorithms with metaheuristic methods transforms sustainable digital architectural design. Key findings include, among others, how such algorithms derive optimal solutions related to energy performance, structural efficiency, and environmental sustainability in architectural and urban design. It confirms that multi-objective optimization models successfully increase the value proposition of design processes through AI-driven approaches, improving predictive accuracy, reducing computation costs, and enabling adjustability in architecture solutions.

The main contribution of this review is the critical synthesis it provides into the vast, varied applications of ML and metaheuristic algorithms; in this way, it also sets a better theoretical framework for their integration into architectural practices. This study underlines some effective methodologies adopted, such as linking generative design to data-driven urban planning, for creating resilient and resourceful built environments. The review further indicates the critical gaps in the literature, especially the need for more empirical and mixed-method studies that would help validate these technologies within practical, real-world contexts. This review sets a baseline for subsequent research to narrow the chasm between theory and application, securing a continued evolution of AI and metaheuristic technologies into beneficial tools within sustainable architecture.

Data Availability Statement

The data presented in this study are available on request from the author.

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Conflicts of Interest

The authors declare no conflict of interest.

Appendix

Appendix A. A Systematic Literature Review on Integrating Machine Learning algorithms and metaheuristic algorithms in optimizing Sustainable Digital Architectural Design

No.	Citation	Major Findings	Methodology Approach	Type of Paper	Data Provider	Journal Name
1	AlAyyash et al. (2023)	SVM-based models with GA and TLBO outperformed ANFIS models in predicting groundwater potential in Jordan's Azraq Basin.	Quantitative	Research Paper	MDPI	Sustainability
2	Lu et al. (2022)	Combined parametric design, machine learning, and GANs for optimizing environmental performance and reducing computational costs in building designs.	Quantitative	Research Paper	MDPI	Energies
3	Chegari et al. (2021)	Multi-objective optimization using ANNs and metaheuristics (NSGA-II, MOPSO) to improve energy performance and indoor thermal comfort in Moroccan residential buildings.	Quantitative	Research Paper	ScienceDirect	Energy and Buildings
4	Alyami et al. (2024)	Applied different metaheuristic algorithms to predict the compressive strength of 3D-printed fiber-reinforced concrete, improving model performance.	Quantitative	Research Paper	ScienceDirect	Developments in the Built Environment
5	Malibari et al. (2022)	Developed an intrusion detection system for smart environments by integrating deep learning with metaheuristics, enhancing security efficiency.	Mixed-Method	Research Paper	ScienceDirect	Sustainable Energy Technologies and Assessments
6	Yi et al. (2019)	Proposed a hybrid metaheuristic algorithm (T-APSSA) for optimizing responsive building facades, improving efficiency in simulation times.	Mixed-Method	Research Paper	MDPI	Sustainability
7	Mahjoubi et al. (2021)	Used automated machine learning and metaheuristics to predict and optimize mechanical and environmental properties of strain-hardening cementitious composites.	Quantitative	Research Paper	ScienceDirect	Journal of Cleaner Production
8	Al-Khazraji et al. (2022)	Introduced a hybrid forecasting model (FA-GRU) to enhance the prediction of concrete block production, outperforming standard GRU and LSTM models.	Quantitative	Research Paper	Scopus	IAES International Journal of Artificial Intelligence
9	Chen et al. (2022)	Utilized Digital Twins and Particle Swarm Optimization (PSO) to improve energy efficiency in CNC milling, reducing energy consumption and improving machining efficiency.	Quantitative	Research Paper	ScienceDirect	Internet of Things and Cyber-Physical Systems
10	Veisi et al. (2022)	Used AI-based solar radiation modeling and multi-objective optimization for urban blocks, achieving high accuracy and reducing computation time.	Quantitative	Research Paper	ScienceDirect	Sustainable Cities and Society
11	Talbi (2021)	Surveyed the integration of machine learning with metaheuristics, providing a detailed taxonomy and identifying research opportunities.	Qualitative	Survey Paper	Scopus	ACM Computing Surveys
12	Ekici et al. (2021)	Developed a multi-zone optimization (MUZO) method for high-rise buildings using AI, improving energy efficiency and daylight metrics during the conceptual design phase.	Quantitative	Research Paper	ScienceDirect	Solar Energy
13	Seyyedabbasi (2023)	Developed a reinforcement learning-based metaheuristic (RLSCSO) to solve global optimization problems, achieving efficient exploration and exploitation in search spaces.	Quantitative	Research Paper	ScienceDirect	Advances in Engineering Software

Appendix A continued

14	Kazeem et al. (2023)	Investigated the role of AI and ML in enhancing construction processes and developing sustainable communities, focusing on energy management and waste reduction.	Qualitative	Review Paper	MDPI	Buildings
15	Huqqani et al. (2023)	Developed a hybrid model combining artificial bee colony and artificial fish swarm algorithms with ANNs to improve landslide susceptibility mapping.	Quantitative	Research Paper	Springer	Engineering with Computers
16	Joshi et al. (2023)	Proposed a hybrid metaheuristic approach combining Deep Belief Networks and Long Short-Term Memory for predicting concrete compressive strength, improving accuracy.	Quantitative	Research Paper	ScienceDirect	Expert Systems with Applications
17	Alkabbani et al. (2021)	Provided a comprehensive review of machine learning and metaheuristics in renewable energy forecasting, focusing on wind and solar power models.	Qualitative	Review Paper	Scopus	Frontiers in Chemical Engineering
18	Ahmed & Darwish (2021)	Introduced a metaheuristic-based CNN architecture optimization method for lightweight and high-accuracy designs, validated on multiple image datasets.	Quantitative	Research Paper	Scopus	IEEE Access
19	Alkhazaleh et al. (2022)	Used hybrid ANFIS models optimized by EO and HHO to predict thermal energy demand, achieving high accuracy compared to benchmark algorithms.	Quantitative	Research Paper	MDPI	Sustainability
20	Saha et al. (2021)	Explored the use of machine learning and metaheuristics for IoT-based sensor data analysis, enhancing smart monitoring applications in diverse domains.	Mixed-Method	Research Paper	Springer	Enabling AI Applications in Data Science
21	Chou & Truong (2021)	Developed a multistep energy consumption forecasting system combining SARIMA and LSSVR, optimized using the Jellyfish Search algorithm for improved accuracy.	Quantitative	Research Paper	Scopus	International Journal of Energy Research
22	Hassaballah et al. (2023)	Combined metaheuristics and machine learning to improve ECG heartbeat classification, achieving 99.92% accuracy in smart healthcare systems.	Quantitative	Research Paper	MDPI	Bioengineering
23	Song et al. (2022)	Reviewed cementitious material mixture optimization using machine learning and metaheuristics, proposing the Beetle Antenna Search algorithm for improved results.	Qualitative	Review Paper	MDPI	Materials
24	Elbeltagi et al. (2023)	Developed a sustainable building optimization model integrating energy simulation, artificial neural networks, and genetic algorithms to reduce energy consumption by 25%.	Quantitative	Research Paper	MDPI	Buildings
25	Azizi et al. (2023)	Proposed the Wolf-Bird Optimizer algorithm for resource tradeoff in BIM-based project scheduling, producing competitive results in construction projects.	Quantitative	Research Paper	ScienceDirect	Journal of Engineering Research
26	Mallick et al. (2021)	Developed ensemble metaheuristic algorithms for landslide risk assessment in Saudi Arabia, achieving high precision in modeling landslide susceptibility zones.	Quantitative	Research Paper	MDPI	Sustainability
27	Ronghui & Liangrong (2022)	Developed a fuzzy-based metaheuristic for optimizing building material strength, energy consumption, and cost in construction management.	Quantitative	Research Paper	Springer	Engineering with Computers
28	Al Duhayyim et al. (2022)	Presented a waste management optimization system using IoT, ResNet-based feature extraction, and AEO for sustainable city planning.	Quantitative	Research Paper	MDPI	Sustainability

Appendix A continued

29	Salami et al. (2023)	Introduced a hybrid machine learning model for predicting energy loads in buildings, achieving high accuracy and explainability using Bayesian optimization and SHAP analysis.	Quantitative	Research Paper	ScienceDirect	Case Studies in Construction Materials
30	Baduge et al. (2022)	Reviewed AI, ML, and DL applications across the construction lifecycle, from design to operation and maintenance, emphasizing the role of smart vision technologies.	Qualitative	Review Paper	ScienceDirect	Automation in Construction
31	Moayedi & Mosavi (2021)	Compared hybrid neural-metaheuristic models for predicting heating loads in residential buildings, identifying the BBO-MLP as the most effective.	Quantitative	Research Paper	MDPI	Sustainability
32	Parvin et al. (2021)	Reviewed intelligent controllers and optimization techniques for building energy management, emphasizing their alignment with sustainable development goals.	Qualitative	Review Paper	Scopus	IEEE Access
33	Ajao & Apeh (2023)	Developed a Petri Net-based reinforcement learning framework for enhancing smart city security, achieving high accuracy in detecting vulnerabilities.	Quantitative	Research Paper	ScienceDirect	Intelligent Systems with Applications
34	Li et al. (2023)	Proposed the SSA-XGB model for predicting compressive strength in green concrete, yielding high accuracy in estimating the performance of sustainable materials.	Quantitative	Research Paper	Springer	Frontiers of Structural and Civil Engineering
35	Sun et al. (2022)	Applied a bio-inspired BAS algorithm to optimize BPNN hyperparameters for predicting the compressive strength of high-strength concrete with excellent accuracy.	Quantitative	Research Paper	MDPI	Buildings
36	Baghdadi et al. (2020)	Proposed an optimized design of prefabricated wall-floor systems using PSO, improving both structural and fabrication efficiency.	Quantitative	Research Paper	ScienceDirect	Automation in Construction
37	Lagaros et al. (2022)	Reviewed the application of 24 different MOAs in structural optimization, showcasing their efficiency in solving complex engineering problems.	Qualitative	Review Paper	Springer	Archives of Computational Methods
38	Hossain et al. (2021)	Developed a multi-objective optimization method for improving indoor thermal comfort and energy performance in residential buildings.	Quantitative	Research Paper	ScienceDirect	Journal of Cleaner Production
39	Kaveh et al. (2023)	Optimized castellated beams using four metaheuristic algorithms, demonstrating cost and structural performance improvements.	Quantitative	Research Paper	Springer	Iranian Journal of Science
40	Ulusoy et al. (2020)	Investigated the use of metaheuristic algorithms for optimizing reinforced concrete beams, finding optimal designs based on concrete strength.	Quantitative	Research Paper	Scopus	Automation in Construction
41	Rane (2023)	Explored the integration of AI, IoT, and big data in the AEC industry, highlighting challenges and future directions for sustainable construction.	Qualitative	Review Paper	Scopus	Engineering and Construction
42	Wu (2021)	Proposed AI-driven communication systems for green hospitals in sustainable cities, improving monitoring and operational efficiency.	Quantitative	Research Paper	ScienceDirect	Sustainable Cities and Society

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