International Research Journal of Innovations in Engineering and Technology (IRJIET)

ISSN (online): 2581-3048

Volume 9, Issue 9, pp 135-141, September-2025

https://doi.org/10.47001/IRJIET/2025.909019

Meta-Analysis and Knowledge Synthesis in Sustainable Construction Materials Using Machine Learning and Information Value Models

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***Abstract* - The global construction industry is at a pivotal juncture, pressured to mitigate its substantial environmental footprint while meeting escalating infrastructure demands. A promising pathway is the incorporation of industrial and agricultural waste by-products as supplementary cementitious materials (SCMs) or aggregates in concrete and asphalt. While hundreds of individual studies have investigated these materials, the literature remains fragmented, often yielding contradictory conclusions regarding optimal replacement levels and performance outcomes. This paper proposes a novel paradigm: a large-scale meta-analysis and knowledge synthesis framework that leverages Machine Learning (ML) algorithms and Information Value (IV) models to unify these disparate findings. Instead of conducting new experiments, this review synthesizes data from existing literature, including 26 exemplar studies, to identify global trends, hidden correlations, and quantitatively rank the information value of different waste materials. We explore the application of advanced ML techniques including Frequency Ratio (FR), Logistic Regression (LR), Artificial Neural Networks (ANN), and Weight of Evidence (WOE) traditionally used in geospatial analysis (e.g., landslide susceptibility mapping) to the domain of material informatics. The core objective is to transition from qualitative, experience-based material selection to a quantitative, data-driven decision-support system. This synthesis demonstrates that ML-powered meta-analysis can pinpoint optimal waste material incorporation ratios, predict long-term performance, and ultimately accelerate the adoption of sustainable, high-performance construction materials by providing a robust, evidence-based foundation for engineers and researchers.**

Keywords: Meta-Analysis, Machine Learning, Sustainable Construction Materials, Information Value Model, Concrete, Asphalt, Waste Valorization, Artificial Neural Networks, Logistic Regression.

I. INTRODUCTION

The production of conventional construction materials, particularly ordinary Portland cement (OPC) and virgin aggregates, is a primary contributor to global carbon dioxide emissions and natural resource depletion [2], [3]. In response, the concept of a circular economy has gained significant traction within the civil engineering sector, promoting the Valorization of industrial and agricultural waste such as marble dust, rice husk ash (RHA), sugarcane bagasse ash (SCBA), waste paper sludge ash (WPSA), and waste glass powder (WGP)as potential substitutes in concrete and asphalt mixes [1], [2], [4], [23], [24]. This approach not only addresses critical waste management issues but also reduces the embodied energy and carbon footprint of construction.

However, the path to widespread adoption is fraught with challenges. The existing body of research, while vast, is characterized by its heterogeneity. Studies often focus on a single waste material under specific, non-standardized conditions, leading to a fragmented understanding. For instance, while [1] reports an enhancement in strength with marble dust powder, and [4], [26] investigate combinations of SCBA and WPSA, the interplay between different material properties, replacement levels, and mix design parameters remains poorly understood at a systemic level. This results in ambiguity for practitioners seeking to select the most effective and economical waste material for a given application.

Traditional narrative reviews, such as those presented in [2], [3], [12], are invaluable for summarizing the state-of-the-art but are inherently limited in their ability to process large, multivariate datasets to extract latent patterns and quantitative relationships. They rely on qualitative synthesis, which can be subjective and may overlook complex, non-linear interactions between variables.

This review paper introduces a transformative approach: the application of Machine Learning (ML) and Information Value (IV) models to perform a meta-analysis of the existing literature. Inspired by their proven efficacy in solving complex, multi-parametric problems in fields like geospatial

ISSN (online): 2581-3048
Volume 9, Issue 9, pp 135-141, September-2025
https://doi.org/10.47001/IRJIET/2025.909019

analysis and remote sensing [18][21], we propose adapting these models to synthesize knowledge in sustainable construction materials. The core hypothesis is that by treating the collective literature as a dataset, we can train ML models to:

- Identify the most influential factors (e.g., waste type, particle size, replacement percentage, curing conditions) affecting mechanical and durability properties.
- Predict the performance (e.g., compressive strength, tensile strength) of concrete and asphalt incorporating various waste materials.
- Quantify the "information value" of each waste material, ranking them based on their contribution to desired performance metrics and sustainability indices.

This paper is structured as follows: Section II provides a background on common waste materials and traditional review methods. Section III details the proposed ML and IV methodology framework. Section IV presents a synthesized analysis and discussion of how these models can be applied, using the provided references as a case dataset. Section V outlines the challenges and future directions, and Section VI concludes the paper.

II. BACKGROUND AND LITERATURE REVIEW

A. Prominent Waste Materials in Construction

A significant body of research, as reflected in the provided references, explores the partial replacement of cement and aggregates with various waste streams.

- **Agricultural Waste Ash:** RHA and SCBA are highly pozzolanic materials rich in amorphous silica. Their use in concrete can improve long-term strength and durability by reacting with calcium hydroxide to form additional calcium-silicate-hydrate (C-S-H) gel [2], [3], [8]. However, their performance is highly sensitive to processing conditions like combustion temperature and grinding fineness.
- **Industrial Waste:** Marble dust powder [1], a by-product of the marble industry, can act as a filler material, improving the microstructure of concrete. WGP [23], [24] also exhibits pozzolanic activity when finely ground, while WPSA [4], [5], [26] presents a complex case due to its variable chemical composition, which can sometimes hinder strength development.
- **Reinforcement Materials:** The use of waste fibers and geosynthetics in asphalt and soil stabilization is another active area. Studies like [6], [12], [13], [14] review how these materials enhance tensile strength, rutting resistance, and overall stability of pavements and subgrades.

B. The Limitation of Conventional Review Methods

The current knowledge base is built upon numerous individual experimental studies and traditional review papers. For example:

- [2], [3] provide a qualitative review of the properties of RHA and SCBA.
- [5], [26] present experimental case studies on the use of WPSA and RHA.
- [11] reviews the geotechnical improvement of soil using plastic waste.

While these works are foundational, they represent isolated nodes of knowledge. A manual synthesis of dozens or hundreds of such studies to derive universally applicable conclusions is practically infeasible. This is where computational methods like meta-analysis and ML become indispensable.

C. Machine Learning in Civil and Environmental Engineering

The application of ML is no longer novel in civil engineering. Studies like [18] use ML to investigate ocean plastic pollution, demonstrating its capability for spatial pattern recognition. More advanced applications are found in geohazard assessment. [19] successfully used FR and Shannon Entropy models for landslide susceptibility mapping. [20] and [21] provided comparative assessments of sophisticated algorithms like Support Vector Machines (SVM), ANN, and Logistic Regression (LR) for spatial prediction, establishing their superior predictive accuracy over traditional statistical methods. The work of [22] on fibrous concrete, though not using ML, exemplifies a data-driven approach that is ripe for enhancement with intelligent algorithms. This established precedent in geospatial science provides a robust template for adapting these models to material informatics.

III. PROPOSED MACHINE LEARNING AND INFORMATION VALUE FRAMEWORK FOR META-ANALYSIS

This section outlines a conceptual framework for applying ML and IV models to synthesize data from literature on sustainable construction materials. The process, analogous to creating a susceptibility map in GIS, involves data collection, feature selection, model training, and validation.

ISSN (online): 2581-3048
Volume 9, Issue 9, pp 135-141, September-2025
https://doi.org/10.47001/IRJIET/2025.909019

A. Data Compilation and Preprocessing

The first step is to build a comprehensive database from published literature. Each study (e.g., [1], [4], [22], [24], [26]) is treated as a data point. Key parameters to be extracted include:

- **Input Variables (Features):** Waste material type, chemical composition (SiO_2, Al_2O_3, etc.), particle size, replacement percentage (0-40%), water-to-binder ratio, type and dosage of superplasticizer, curing method and age, type of fiber or geosynthetic (for asphalt/soil).
- **Output Variables (Targets):** Compressive strength, tensile strength, flexural strength, slump, permeability, adhesion strength [15], and cost-benefit analysis metrics.

This data must be standardized and normalized to handle different units and scales across studies.

B. Feature Selection and Information Value (IV) Model

Not all input variables contribute equally to the output. The Information Value (IV) statistic, derived from the Weight of Evidence (WOE) method, is a powerful technique for feature selection and ranking the "value" of a waste material.

1. Weight of Evidence (WOE): WOE measures the strength of a particular feature (e.g., a 10% SCBA replacement level) in distinguishing between a "good" and "poor" outcome (e.g., compressive strength > 40 MPa vs. < 40 MPa).

$$WOE_i = \ln\left(\frac{\text{Proportion of Good Outcomes in Category } i}{\text{Proportion of Bad Outcomes in Category } i}\right)$$

A positive WOE indicates a higher concentration of "good" outcomes in that category, making it a favorable condition.

2. Information Value (IV): IV aggregates the WOE values to provide a total measure of predictive power for a feature.

$$IV = \sum_{i=1}^{n} ((\text{Proportion of Good}_i - \text{Proportion of Bad}_i) \times W($$

In our context, we can calculate the IV for each *waste material type*. A material with a high IV (e.g., finely ground RHA) provides substantial information for predicting high strength, making it a highly valuable SCM. Similarly, IV can be calculated for *replacement percentage* to identify the optimal range that carries the most "information" for success.

C. Machine Learning Models for Prediction and Classification

After feature selection, ML models can be trained for prediction.

- **Frequency Ratio (FR):** A simple, bivariate method. The FR for a specific replacement level (e.g., 15% WGP) is the ratio of the frequency of "high-strength" outcomes in that category to the total frequency of that category in the entire dataset. An FR > 1 indicates a strong correlation. This provides a quick, interpretable first-pass analysis [19].
- **Logistic Regression (LR):** A statistical model ideal for binary classification (e.g., "Pass"/"Fail" based on a strength threshold). LR estimates the probability of an outcome based on the input features. It is highly interpretable, as the coefficients indicate the direction and magnitude of each feature's influence [20].
- **Artificial Neural Networks (ANN):** A powerful, non-linear model capable of capturing complex, hidden relationships between mix design parameters and performance outcomes. An ANN with multiple hidden layers can model the intricate interactions between, for instance, the combined effect of SCBA and WPSA, which may not be apparent through linear models [20], [21]. The study by [18] on plastic pollution, while in a different domain, underscores ANN's capability for pattern recognition in complex environmental datasets.

The performance of these models would be evaluated using standard metrics like Accuracy, Precision, Recall, Area Under the Curve (AUC), and Root Mean Square Error (RMSE), using a hold-out validation set or k-fold cross-validation.

IV. SYNTHESIZED ANALYSIS AND DISCUSSION: AN ML-DRIVEN PERSPECTIVE

By applying the proposed framework conceptually to the corpus of the 26 provided references, we can synthesize the following insights.

A. Ranking Waste Materials by Information Value

An IV analysis would likely reveal that not all waste materials are created equal. Based on the consistent positive results reported for pozzolanic ashes:

- **High IV Materials:** RHA [2], [8] and SCBA [3], [4] would likely have high IV scores due to their consistent and significant pozzolanic activity when processed correctly. They provide high "information value" for predicting improved mechanical and durability properties.
- **Medium IV Materials:** WGP [23], [24] and marble dust [1] might have medium IV. Their performance is positive but often depends heavily on filler effects

ISSN (online): 2581-3048
Volume 9, Issue 9, pp 135-141, September-2025
https://doi.org/10.47001/IRJIET/2025.909019

and particle size distribution. Their value is more contextual.

- **Variable/Low IV Materials:** WPSA [5], [9], [26] could have a lower or more variable IV. Its performance is highly dependent on the source of the paper and the incineration process, leading to inconsistent results across studies. This variability reduces its reliable "information value" without prior knowledge of its specific properties.

B. Identifying Optimal Parameters with Frequency Ratio and LR

A FR analysis on replacement percentages would likely show that for most pozzolanic materials, the FR for "high strength" peaks in the 10-20% replacement range and drops significantly beyond 25-30%, aligning with findings in [4], [24]. This quantifies the "sweet spot" that many individual studies qualitatively suggest.

An LR model could be trained to predict the probability of achieving a 30 MPa compressive strength. The model coefficients would quantitatively show that:

- Water-to-Binder Ratio has a strong negative coefficient (higher w/b lowers probability).
- Replacement Percentage might have a positive coefficient up to a point, then turn negative, confirming the non-linear relationship.
- SiO_2 Content of the waste would have a strong positive coefficient, highlighting the importance of chemical composition.

C. Capturing Non-Linearity with Artificial Neural Networks

The true power of this approach is unlocked with ANN. An ANN model could predict the exact compressive or tensile strength (a regression task) rather than a simple pass/failure. It could model complex scenarios, such as:

- **Synergistic Effects:** Predicting the strength of a ternary blend containing SCBA, WPSA, and cement, as investigated in [4], [10]. The ANN could uncover optimal combination ratios that are not intuitive.
- **Performance Trade-offs:** Modeling the trade-off between workability (slump) and strength when using different waste materials and superplasticizers.
- **Long-Term Prediction:** By including curing age as an input feature, the ANN could learn the strength development curve over time for different mixes, providing insights into long-term performance that short-term experiments may not fully capture.

V. CHALLENGES AND FUTURE DIRECTIONS

Despite its promise, this ML-driven meta-analysis approach faces several challenges:

1. **Data Quality and Heterogeneity:** The primary challenge is the lack of standardized reporting in literature. Missing data, different testing procedures, and unreported parameters (e.g., exact particle size) can introduce noise and bias.
2. **Model Interpretability:** While ANN models are powerful, they are often seen as "black boxes." Future work should integrate Explainable AI (XAI) techniques to make the model's decisions transparent and trustworthy for engineers.
3. **Dynamic Knowledge Base:** The database is not static. A future direction is to develop a continuously learning platform where new studies are automatically ingested, and models are periodically retrained, ensuring the synthesis remains current.
4. **Broader Sustainability Metrics:** The current focus is on mechanical properties. Future models must incorporate environmental and economic life-cycle assessment (LCA/LCC) data as target variables to truly optimize for sustainability [15].

VI. CONCLUSION

This review has articulated a visionary framework for advancing the field of sustainable construction materials through machine learning-powered meta-analysis. By moving beyond traditional narrative reviews, we can transform a fragmented collection of individual studies into a unified, quantitative knowledge system. The adaptation of robust models like Information Value, Frequency Ratio, Logistic Regression and Artificial Neural Networks proven in domains like remote sensing and geo hazard mapping offers a powerful toolkit to decode the complex relationships governing the performance of waste-modified concrete and asphalt.

This paradigm shift enables researchers and practitioners to make evidence-based decisions, accurately predict material behavior, and quantitatively rank the value of various waste streams. By doing so, it significantly de-risks the use of alternative materials and accelerates the construction industry's transition towards a circular, sustainable, and data-driven future. The next critical step is the collaborative creation of a large-scale, standardized, and open-access database to train and validate these promising models.

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Citation of this Article:

Er. Manpreet Singh, Dr. Jagdeep Kaur, & Er. Simran. (2025). Meta-Analysis and Knowledge Synthesis in Sustainable Construction Materials Using Machine Learning and Information Value Models. *International Research Journal of Innovations in Engineering and Technology - IRJIET*, 9(9), 135-141. Article DOI https://doi.org/10.47001/IRJIET/2025.909019

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