Bulletin of Electrical Engineering and Informatics
Vol. 14, No. 6, December 2025, pp. 4925~4934
ISSN: 2302-9285, DOI: 10.11591/eei.v14i6.10598

Prediction of asphalt performance based on plastic waste using machine learning

I Gusti Agung Ananda Putra[1], Darpan Rokade[2]
[1]Environmental Engineering, Faculty of Engineering and Informatics, Universitas Pendidikan Nasional, Denpasar, Indonesia
[2]Computer Science, Faculty of Computer Science, P.E.S. Modern College of Arts, Science and Commerce, Pune, India

Article Info

Article history:

Received Apr 29, 2025
Revised Aug 19, 2025
Accepted Sep 27, 2025

Keywords:

Asphalt mixtures
Machine learning
Performance prediction
Plastic waste
Sustainable road construction

ABSTRACT

The incorporation of plastic waste into asphalt mixtures offers a promising solution to address the growing environmental concerns while enhancing the performance of road materials. Traditional methods, such as the Marshall test, are costly and time-consuming, thus highlighting the need for more efficient prediction techniques. Machine learning (ML) models, including random forest (RF), extreme gradient boosting (XGBoost), and artificial neural networks (ANN), have shown significant potential in predicting asphalt performance, optimizing material compositions, and reducing the dependence on labor-intensive laboratory tests. Key influencing factors such as bitumen content, plastic size, and temperature have been identified as crucial for improving asphalt properties. This systematic review emphasizes the potential of ML in streamlining the development of plastic-modified asphalt, offering a sustainable and cost-effective approach to road construction. Furthermore, it supports the advancement of green infrastructure and lays the foundation for future innovations in sustainable pavement engineering, contributing both to academic research and practical applications in the construction industry.

Corresponding Author:

I Gusti Agung Ananda Putra
Environmental Engineering, Faculty of Engineering and Informatics, Universitas Pendidikan Nasional
Denpasar, Indonesia
Email: anandaputra@undiknas.ac.id

1. INTRODUCTION

The global issue of plastic waste has reached a concerning level, with annual production exceeding 359 million tonnes, causing serious environmental and health issues [1]. The magnitude of plastic pollution is further highlighted by studies showing that a significant portion of this waste enters oceans, exacerbating ecological damage [2]. The road construction sector emerges as a potential solution for utilising plastic waste by incorporating it as a reinforcement material in asphalt, thereby reducing environmental burdens while enhancing material performance [3]. Early demonstrations in countries like India have validated the technical feasibility of plastic roads, showcasing enhanced durability under tropical conditions [4]. However, the variability in the physicochemical properties of plastics and the uncertainties surrounding their interactions with bitumen present challenges in designing optimal mixtures [5]. Chemical incompatibilities between certain plastics and bitumen can lead to phase separation, necessitating rigorous pre-treatment protocols [6]. Empirical studies demonstrate that incorporating waste plastics such as polyethylene terephthalate (PET), low-density polyethylene (LDPE), and high-density polyethylene (HDPE) into hot mix asphalt can enhance Marshall stability and flow properties, indicating improved mechanical performance with increasing plastic content [7]. Field trials confirm that polyethylene-modified asphalt exhibits superior resistance to cracking compared to conventional mixes [8]. Furthermore, the conventional Marshall method for estimating bitumen ratios is costly and time-consuming [9]. Recent advances propose machine learning (ML) as a viable alternative to empirical methods, reducing testing time [10]. Consequently, there is a pressing need for more efficient and accurate approaches to predict the performance of plastic-modified asphalt [11]. This challenge has prompted the exploration of ML techniques as an innovative solution.

Increasing vehicular traffic accelerates pavement deterioration, highlighting the need for improved road planning and construction [12]. Incorporating plastic waste into asphalt can reduce greenhouse gas emissions by up to 10% while enhancing cost-effectiveness and sustainability [13]. Despite adoption of advanced technologies in developing countries, gaps in standardization and regulations especially in regions with informal waste systems lead to inconsistent outcomes [14], [15]. Failures to predict parameters like rutting and fatigue life increase repair costs [16]. ML can optimize mixtures, reducing dependence on costly lab tests, with neural networks accurately predicting rutting depth and enabling real-time adjustments [17], [18]. Integrating ML thus addresses technical challenges and advances sustainable development goals amid global demands for green infrastructure and a circular economy [19].

Previous studies have explored the use of plastics such as PET, LDPE, and HDPE in hot asphalt mixtures. Ma *et al.* [5] summarized both opportunities and technical challenges of utilizing plastic waste, while Shah *et al.* [7] demonstrated that plastic additives enhance Marshall stability and deformation resistance. Liu *et al.* [17] and Jamil *et al*. [20] further emphasized the importance of ML-based methods for predicting performance parameters of modified asphalt, extending to model interpretability through Shapley additive explanations (SHAP) analysis. Limited ML use and reliance on conventional lab methods, combined with material variability and protocol gaps, hinder generalizability and slow sustainable asphalt technology adoption.

Despite progress in plastic waste-based asphalt research, most studies still rely on traditional laboratory methods like the Marshall test, rutting tests, and temperature/humidity resistance evaluations [21], [22], which are inefficient for exploring complex mixture compositions and accommodating the variability of plastic waste inputs [23], [24]. Few studies have applied ML to predict asphalt performance, with most being limited to conventional asphalt without plastic waste [25]. Furthermore, aspects of model interpretability, such as the use of SHAP, are still rarely applied in this context [20]. Explainable artificial intelligence (AI) techniques like SHAP are critical for regulatory adoption, as they demystify "black-box" predictions [26]. A research gap exists in applying ML to fully predict plastic waste-based asphalt performance. A systematic review is needed to map developments and guide future research in sustainable pavement engineering.

In the landscape of modern civil engineering research, soft computing techniques, such as artificial neural networks (ANN), have been effectively applied to predict the permanent axial deformation of asphalt concrete pavements [27]. Models such as random forest, support vector regression, and extreme gradient boosting (XGBoost) have proven capable of capturing complex relationships between input variables and outputs [20]. In the context of plastic waste-based asphalt, the ability of these models to handle heterogeneous data is particularly relevant, given the non-uniform and difficult to control nature of the waste [28]. However, no systematic review has yet mapped ML applications for plastic waste-based asphalt, highlighting a gap in structured guidance for research development [25], [29]. A systematic review can classify previous studies by methods, data, models, and outcomes, identify trends and gaps, and facilitate cross-disciplinary knowledge transfer between materials science, road engineering, and AI [30], [31].

This research is highly relevant as it addresses two strategic issues: waste reduction and smart infrastructure development [32]. Globally, sustainable road projects increasingly require predictive approaches for cost and time efficiency [33]. Integrating ML into plastic waste-based asphalt development enables both performance prediction and material composition optimization using historical and physical data [30], [34]. The growing number of related publications underscores its academic and practical significance [22]. The primary objective is a systematic literature review on ML applications for predicting the performance of plastic-modified asphalt, identifying models used, key parameters, and their accuracy [17]. By categorizing studies by year, method, and data type, this review maps research development, evaluates model strengths and weaknesses, and provides recommendations for future work [27]. Focusing on articles from 2022–2025 indexed in Scopus, the study aims to support the development of adaptive, transparent, and implementable prediction systems [20], integrating pavement engineering, materials science, and data science to address challenges in plastic waste management and sustainable road construction.

This systematic review offers both theoretical and practical contributions. It enriches the literature on ML in road engineering [27] and provides insights for engineers, policymakers, and the construction industry to promote environmentally friendly technologies [32]. The findings can inform standards for using plastic waste in road construction and support evidence-based development of data-driven predictive models for asphalt performance [20], facilitating faster progress toward green and efficient infrastructure [22]. This systematic literature review examines the application of ML in predicting the performance of plastic-modified asphalt. The study focuses on comparing different model types, influential parameters, and their accuracy. Its contributions are expected to benefit both academia and industry by mapping current research and providing recommendations with potential impacts on environmental policies. The study's novelty lies in three key areas: it uses a curated, multi-source dataset; it applies interpretability tools like SHAP to make the models transparent; and it compares multiple ML algorithms to identify the most reliable method.

2. METHOD

2.1. Identification

The researcher conducted a systematic review following the guidelines [35], [36]. The review process consisted of three stages: identification, selection, and inclusion. The activities in the identification stage involved determining the specific research context, establishing the review protocol, and formulating the research questions. As shown in Figure 1, the researcher needed to identify the objectives and develop the research questions. Furthermore, the review protocol was established by the researcher during this stage. Issues related to plastic waste-based asphalt were selected as the main context of this study. The rationale for selecting this approach is twofold:

a. Scientific justification: to map and synthesize the fragmented body of knowledge on ML applications in asphalt performance prediction.
b. Practical justification: to provide practitioners with evidence-based insights into the most accurate models, influential parameters, and potential research gaps.

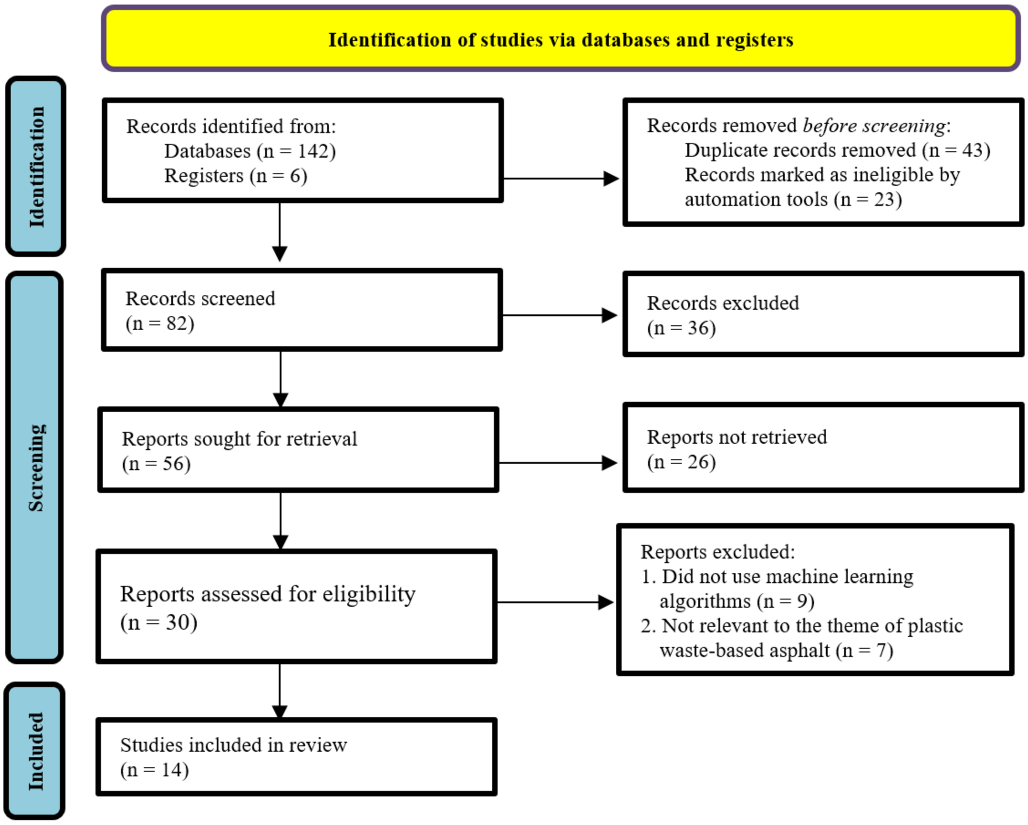

Figure 1. Systematic literature review process

2.2. Screening

The literature search was conducted in Scopus, IEEE Xplore, Google Scholar, and Elsevier (2022–2025) using the keywords: "plastic waste asphalt" and "machine learning prediction." The dataset used in this study was obtained from previously published experimental data on asphalt mixtures modified with plastic waste, comprising a total of 14 asphalt mixture samples with varying compositions. It includes three types of plastic waste (PET, HDPE, and LDPE) with contents ranging from 2% to 10% by weight of bitumen, penetration grade 60/70 bitumen, and aggregate sizes between 5–20 mm. The selection criteria are presented in Table 1. To ensure the comprehensiveness of the review, multiple databases were selected to capture both engineering-focused and multidisciplinary studies, thereby minimizing publication bias and improving coverage of relevant research [37], [38].

Table 1. Article selection criteria

No.	Criteria	Inclusion	Exclusion
1	Topic	Plastic waste asphalt and ML prediction	Articles that do not focus on plastic waste-based asphalt and ML prediction were excluded.
2	Journal published	Top publisher: Scopus, IEEE Xplore, Google Scholar, and Elsevier	Journal and conference paper outside of the top publisher/source
3	Publication date	2022-2025	Before 2022
4	Publication type	Journal and conference paper	Dissertations, technical reports, and book chapters
5	Language	English	Non-English

2.3. Included

The author analyzed articles that satisfied the criteria outlined above for further evaluation in accordance with the inclusion requirements of the review. Duplicates were removed at this stage. In addition, the relevance of each article was reviewed, using the title and abstract as the primary criteria. Data extraction was evaluated for its completeness and usefulness using a quality assessment. To ensure the quality of the literature analyzed in this study, the researcher conducted an evaluation of each article using five main indicators: (A) topic relevance, (B) clarity of research objectives, (C) primary data, (D) analysis methods, and (E) model structure. Each indicator was scored either 0 (does not meet the criterion) or 1 (meets the criterion), with a maximum possible score of 5 points. This assessment determined each article's eligibility for further analysis [39], as shown in Table 2, aligning with scoring frameworks commonly used in systematic reviews to enhance transparency and reduce bias [40].

Table 2. Article quality assessment

No.	Sources	A	B	C	D	E	Total score	Description
1	Author 1 (2020)	1	1	1	1	1	5	Highly eligible
2	Author 2 (2021)	1	1	1	1	0	4	Eligible
3	Author 3 (2022)	1	1	1	0	0	3	Moderately eligible
4	Author 4 (2023)	1	1	0	0	0	2	Ineligible
5	Author 5 (2024)	1	0	0	0	0	1	Highly ineligible

2.4. Research questions and knowledge gaps

The methodological framework was designed to answer the following:

- What ML models are most frequently used and which show the highest predictive accuracy?
- What are the most influential parameters in predicting asphalt performance?
- What limitations exist in current research, and how can they guide future studies?

By systematically following this process, the study ensures that the results section directly addresses the research gaps identified in the introduction namely the lack of comprehensive application of ML in plastic waste-modified asphalt and the limited exploration of interpretable AI approaches.

3. RESULTS AND DISCUSSION

3.1. Analyze the existing published

Out of 30 articles filtered for quality, 14 (46.67%) met the criteria and were used for evidence synthesis. The selected papers' abstracts and content were further evaluated to ensure relevance to the research (see Table 3).

A total of 14 articles were analyzed in this study, with the highest publication distribution in 2023 (6 articles, 42.86%), followed by 2024 (3 articles, 21.43%), 2025 (3 articles, 21.43%), and the remaining from 2022 (1 article, 7.14%) (Figure 2). Based on the research type, the proportion between conceptual and empirical articles was balanced, with 7 articles in each category, representing 50% of the total. In terms of publication type, 13 articles (92.86%) were published in scientific journals, while 1 article (7.14%) was from conference proceedings. Regarding the publishers, Elsevier was the most dominant publisher, with 8 articles (57.14%), followed by Scopus-indexed non-Elsevier articles (4 articles, or 28.57%). One article was published through Google Scholar and one through IEEE Xplore (both 7.14%). The literature is mainly recent, from reputable journals, and balanced between conceptual and empirical studies, enhancing the credibility and relevance of the research.

Table 3. Provides an overview of the quality assessment

No.	Sources	Year	Type of research	Type of article	Publisher
1	[20]	2025	Conceptual	Journal	Elsevier
2	[41]	2025	Conceptual	Journal	Elsevier
3	[30]	2025	Empirical	Journal	Scopus
4	[42]	2024	Empirical	Journal	Google Scholar
5	[43]	2024	Conceptual	Journal	Elsevier
6	[44]	2024	Empirical	Journal	Elsevier
7	[45]	2024	Empirical	Journal	Scopus
8	[32]	2023	Conceptual	Journal	Elsevier
9	[29]	2023	Conceptual	Journal	Elsevier
10	[46]	2023	Empirical	Journal	Elsevier
11	[47]	2023	Conceptual	Journal	Scopus
12	[48]	2023	Empirical	Journal	Elsevier
13	[25]	2023	Empirical	Journal	Scopus
14	[28]	2022	Conceptual	Conferences	IEEE Xplore

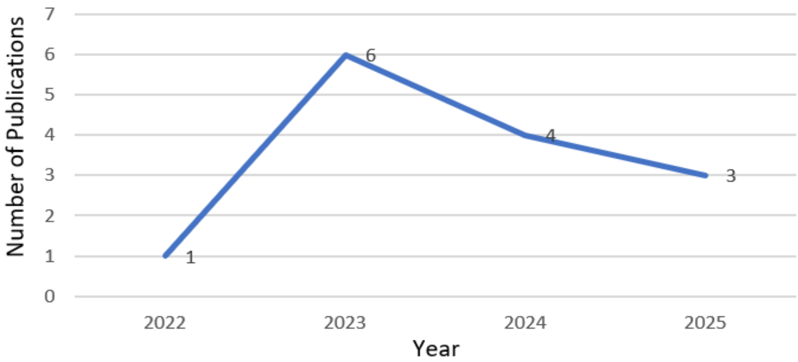

Figure 2. Research trend

3.2. Quality assessment result

The 14 articles were evaluated on five indicators topic relevance, research objectives, primary data, analysis methods, and model structure using a binary scoring system. Most scored 4 or 5, making them eligible to highly eligible references, while only one was moderately eligible (score 3) (see Table 4). A total of 7 articles (50%) were categorized as highly eligible, 6 articles (42.86%) as eligible, and only 1 article (7.14%) was categorized as moderately eligible. No articles were classified as ineligible or highly ineligible. The literature is of high methodological and substantive quality, supporting the validity of the study's analysis and discussions. The overall distribution of article quality is presented in Table 5.

Table 4. Quality assessment result

No.	Sources	A	B	C	D	E	Total score	Description
1	[20]	1	1	0	1	1	4	Eligible
2	[41]	1	1	0	1	1	4	Eligible
3	[30]	1	1	1	1	1	5	Highly eligible
4	[42]	1	1	1	1	1	5	Highly eligible
5	[43]	1	1	0	1	0	3	Moderately eligible
6	[44]	1	1	1	1	1	5	Highly eligible
7	[45]	1	1	1	1	1	5	Highly eligible
8	[32]	1	1	0	1	1	4	Eligible
9	[29]	1	1	0	1	1	4	Eligible
10	[46]	1	1	1	1	1	5	Highly eligible
11	[47]	1	1	0	1	1	4	Eligible
12	[48]	1	1	1	1	1	5	Highly eligible
13	[25]	1	1	1	1	1	5	Highly eligible
14	[28]	1	1	0	1	1	4	Eligible

Table 5. Summary of research findings

Article quality	Highly ineligible (1)	Ineligible (2)	Moderately eligible (3)	Eligible (4)	Highly eligible (5)	Total
No articles	0	0	1	6	7	14
Percentages (%)	0	0	7.14	42.86	50	100

3.3. Data analysis

Ensemble ML models like XGBoost, categorical boosting (CatBoost), random forest, and ANN consistently perform best in predicting asphalt properties, with high R^2 values (ranging from approximately 0.87 to 0.9999). Ensemble methods outperform singular models due to their ability to handle nonlinear interactions in composite materials [49]. Key influential factors include bitumen content (around 5%), plastic size, bitumen volume, sand size, fiber content, and temperature/frequency variables. Optimal bitumen ratios depend on plastic type and climate [50]. Techniques like SHAP, GeoGNN, and multi-expression programming (MEP) are increasingly used for model interpretation and advanced prediction. ML applications in asphalt mixture optimization are rapidly advancing, enabling recycled materials use and more transparent modeling (see Table 6). Figure 3 shows that ensemble models (CatBoost R^2=0.99, random forest R^2=0.97, XGBoost R^2=0.95) and ANN (R^2=0.9999) achieved the highest predictive accuracy for asphalt properties, while support vector machine (SVM) (R^2=0.88), gene expression programming (GEP) (R^2=0.93), and Bagging (R^2=0.92) performed moderately. This highlights ensemble learning and neural networks as the most effective for modeling plastic-modified asphalt.

Table 6. Research on plastic waste-based asphalt using ML

No.	Source	Models used	Results
1	[20]	Random forest (RF), gradient boosting, XGBoost, and bagging regressor (BR)	XGBoost performed well (R^2=0.95 train; 0.84 test), driven mainly by plastic size and bitumen content.
2	[41]	GeoGNN and ML traditional	GeoGNN achieved the highest accuracy.
3	[30]	ANN, SVM, GP, and REP tree	ANN achieved the best performance (R^2=0.9999), mainly influenced by bitumen content and volume.
4	[42]	MEP	MEP was accurate, with sand size and fiber content influencing compressive strength by more than 50%.
5	[43]	ANN, SVM, and gradient boosting	ANN and SVR were effective, with biodegradable PCM showing strong potential for thermal energy storage.
6	[44]	Gene expression programming	GEP models accurately predict rutting depth.
7	[45]	MLP, RBFNN, GRNN, and SVM	An MLP model performed best with an R^2 of 0.98.
8	[32]	CatBoost, XGBoost, LightGBM, and RF	CatBoost showed the best accuracy.
9	[29]	Decision tree, AdaBoost, and Bagging	BR provided the best performance.
10	[46]	Gene expression programming	Sand size and fiber content being the dominant factors (>50% influence).
11	[47]	SHAP and ML modeling (ANN, SVR, and XGBoost)	The type and content of plastic, as well as the aggregate gradation, had the most significant influence.
12	[48]	SVM, GP, RF, random tree (RT), and M5P model tree	Random forest performed the best with a correlation coefficient (CC) of 0.9735. The binder content of 5% was the most influential factor.
13	[25]	SVM and CatBoost	CatBoost performed excellently (R^2=0.9916).
14	[28]	ANN, SVM, GP, and RF	SVM showed the best performance with a CC of 0.8776.

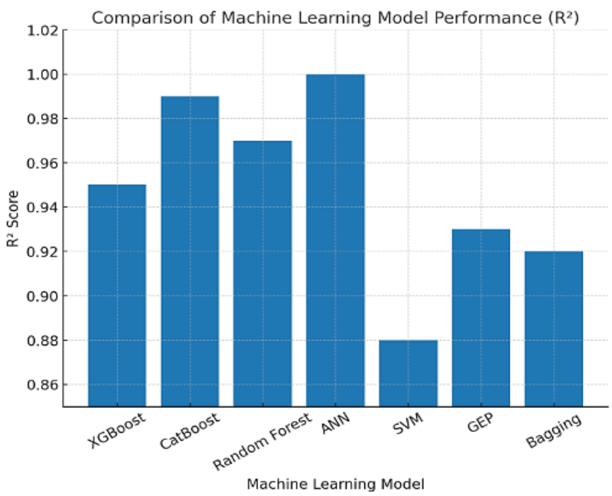

Figure 3. Comparison of ML model performance

The feature importance analysis of the random forest model in Figure 4 shows that in the random forest model, plastic type and plastic content drive nearly 70% of predictions, highlighting their dominant role in asphalt stability and flow. Bitumen content has moderate influence, while aggregate size contributes least, emphasizing the importance of optimizing plastic selection and proportion for performance. All ML models were systematically tuned for optimal performance. Tree-based models (decision tree, random forest, and XGBoost) used grid search with k-fold cross-validation to optimize depth, tree count, and learning rate. SVM parameters (kernel, C, and γ) were iteratively adjusted, while ANN hyperparameters (hidden layers, neurons, and learning rate) were tuned with early stopping. This improved model generalization and prediction reliability.

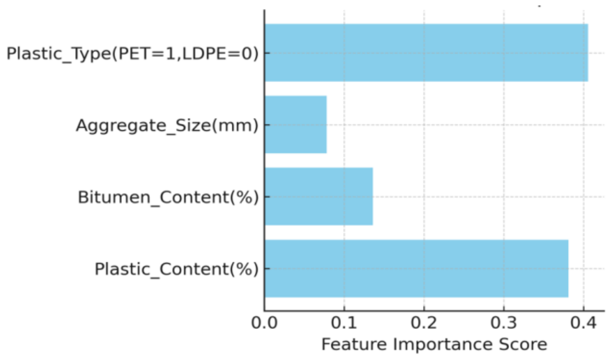

Figure 4. Feature importance

3.4. Discussion

Previous studies on plastic waste-modified asphalt have relied on costly, time-consuming laboratory tests [21], [22]. This research addresses that gap by using ML, finding that models like ensemble methods and ANNs consistently achieve high predictive accuracy (R^2>0.95) [25], [30], [44]. While ANNs are highly accurate (R^2>0.99) [30], their "black-box" nature makes them less suitable for regulation than more transparent models like random forest [25], [26]. The most significant factors influencing performance are bitumen content, plastic size, temperature, and loading frequency [29], [49], [50]. However, the study has limitations because most models were trained on controlled lab data [24], [49], which may not generalize to real-world conditions [15], [23]. The lack of international standards for plastic-bitumen ratios limits reproducibility. ML can enhance pavement design by reducing costs and improving forecast reliability, supporting eco-friendly technologies and SDGs. Future research should incorporate large scale field data, digital twins, and multi-objective optimization [18], [32].

This study has several limitations, including a limited and region-specific dataset from published experiments, which restricts the models' generalizability. The predictions also lack validation under real pavement conditions, and the long-term durability of the material is uncertain. Future research should therefore conduct field trials, integrate in-situ monitoring, and establish pilot projects to strengthen the correlation between ML predictions and actual pavement behavior over time. This study's predictive models can be integrated with electrical engineering and informatics to create smart pavement technologies. By deploying sensor-based monitoring systems and implementing the ML models on cloud-based platforms or mobile applications, real-time predictions can be made accessible to engineers, contractors, and municipal planners. This integration would enable more efficient decision-making in mixture design, field monitoring, and infrastructure planning, strengthening the research's contribution to sustainable road management.

4. CONCLUSION

Integrating plastic waste into asphalt offers environmental and engineering benefits, while ML models like random forest, XGBoost, and ANN efficiently predict performance, with bitumen content, plastic size, and temperature as key factors. ML can reduce costs, speed project delivery, and support green infrastructure. Future work should validate models in real-world conditions, use explainable AI, and establish global standards for practical implementation. In the field, they may be linked with sensor-based monitoring to track pavement conditions and detect early signs of failure, making them useful for sustainable road management and decision-making.

ACKNOWLEDGMENTS

The authors would like to thank Universitas Pendidikan Nasional for the support of this research.

FUNDING INFORMATION

The publication of this article also contributes to the research reward.

AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
I Gusti Agung Ananda Putra	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓		✓	✓
Darpan Rokade	✓	✓	✓	✓	✓	✓	✓			✓			✓	

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author.

REFERENCES

[1] P. G. C. N. T. Pilapitiya and A. S. Ratnayake, "The world of plastic waste: a review," *Cleaner Materials*, vol. 11, p. 100220, Mar. 2024, doi: 10.1016/j.clema.2024.100220.

[2] J. R. Jambeck *et al.*, "Plastic waste inputs from land into the ocean," *Science*, vol. 347, no. 6223, pp. 768–771, 2015, doi: 10.1126/science.1260352.

[3] C. A. Vargas, H. R. Lu, and A. El Hanandeh, "Environmental impact of pavements formulated with bitumen modified with pe pyrolytic wax: a comparative life cycle assessment study," *Journal of Cleaner Production*, vol. 419, 2023, doi: 10.1016/j.jclepro.2023.138070.

[4] R. K. Pawar and B. D. P. Patil, "Utilization of waste plastic in tiles," *International Journal of Engineering and Advanced Technology*, vol. 12, no. 4, pp. 19–24, Apr. 2023, doi: 10.35940/ijeat.C4028.0412423.

[5] Y. Ma *et al.*, "The utilization of waste plastics in asphalt pavements: a review," *Cleaner Materials*, vol. 2, pp. 1-13, Dec. 2021, doi: 10.1016/j.clema.2021.100031.

[6] A. B. Ameur, J. Valentin, and N. Baldo, "A review on the use of plastic waste as a modifier of asphalt mixtures for road constructions," *CivilEng*, vol. 6, no. 2, pp. 1-31, Apr. 2025, doi: 10.3390/civileng6020017.

[7] M. M. Shah, J. Yousaf, U. Khalid, H. Li, J.-J. Yee, and S. A. Z. Naqvi, "Plastic roads: asphalt mix design and performance," *Discover Applied Sciences*, vol. 6, no. 4, pp. 1-21, Apr. 2024, doi: 10.1007/s42452-024-05772-x.

[8] F. Yin, M. Fortunatus, R. Moraes, M. D. Elwardany, N. Tran, and J. P. Planche, "Performance evaluation of asphalt mixtures modified with recycled polyethylene via the wet process," *Transportation Research Record*, vol. 2675, no. 10, pp. 491–502, 2021, doi: 10.1177/03611981211011650.

[9] M. Y. Çodur, H. B. Kasil, and E. Kuşkapan, "Estimating the bitumen ratio to be used in highway asphalt concrete by machine learning," *The Baltic Journal of Road and Bridge Engineering*, vol. 19, no. 2, pp. 23–42, Jun. 2024, doi: 10.7250/bjrbe.2024-19.634.

[10] T. Tamagusko, M. G. Correia, and A. Ferreira, "Machine learning applications in road pavement management: a review, challenges and future directions," *Infrastructures*, vol. 9, no. 12, p. 213, Nov. 2024, doi: 10.3390/infrastructures9120213.

[11] K. Ijari and C. D. Paternina-Arboleda, "Sustainable pavement management: harnessing advanced machine learning for enhanced road maintenance," *Applied Sciences (Switzerland)*, vol. 14, no. 15, pp. 1-17, 2024, doi: 10.3390/app14156640.

[12] A. Nurhidayat and K. H. Bin Kamarudin, "A systematic review of the impact overload on road pavement batu city, indonesia," *International Journal of Transport Development and Integration*, vol. 8, no. 1, pp. 49–60, Mar. 2024, doi: 10.18280/ijtdi.080105.

[13] I. Elnaml, J. Liu, L. Mohammad, H. Dylla, N. Wasiuddin, and S. Cooper, "Recycling waste plastics in asphalt mixture: engineering performance and environmental assessment," *Journal of Cleaner Production*, vol. 453, 2024, doi: 10.1016/j.jclepro.2024.142180.

[14] A. Raj, G. Dwivedi, A. Sharma, A. B. L. de S. Jabbour, and S. Rajak, "Barriers to the adoption of industry 4.0 technologies in the manufacturing sector: an inter-country comparative perspective," *International Journal of Production Economics*, vol. 224, p.

107546, Jun. 2020, doi: 10.1016/j.ijpe.2019.107546.
[15] A. Chapman, K. K. Sen, T. Mochida, Y. Yoshimoto, and K. Kishimoto, "Overcoming barriers to proactive plastic recycling toward a sustainable future," *Environmental Challenges*, vol. 17, pp. 1-10, 2024, doi: 10.1016/j.envc.2024.101040.
[16] I. D. Uwanuakwa, S. I. A. Ali, M. R. M. Hasan, P. Akpinar, A. Sani, and K. A. Shariff, "Artificial intelligence prediction of rutting and fatigue parameters in modified asphalt binders," *Applied Sciences (Switzerland)*, vol. 10, no. 21, pp. 1–17, 2020, doi: 10.3390/app10217764.
[17] J. Liu, F. Liu, C. Zheng, D. Zhou, and L. Wang, "Optimizing asphalt mix design through predicting the rut depth of asphalt pavement using machine learning," *Construction and Building Materials*, vol. 356, 2022, doi: 10.1016/j.conbuildmat.2022.129211.
[18] J. Wang, R. Zhang, H. Zhou, W. Huang, D. Feng, and X. Li, "Optimization of asphalt mix design considering mixture performance, environmental impact, and life cycle cost," *Journal of Cleaner Production*, vol. 512, p. 145618, Jun. 2025, doi: 10.1016/j.jclepro.2025.145618.
[19] K. O. Babaremu *et al.*, "Sustainable plastic waste management in a circular economy," *Heliyon*, vol. 8, no. 7, pp. 1-6, 2022, doi: 10.1016/j.heliyon.2022.e09984.
[20] M. H. Jamil, R. Jagirdar, A. Kashem, M. N. Ali, and D. Deb, "Modeling of marshall stability of plastic-reinforced asphalt concrete using machine learning algorithms and shap," *Hybrid Advances*, vol. 10, pp. 1-12, Sep. 2025, doi: 10.1016/j.hybadv.2025.100483.
[21] A. F. Al-Shawabkeh, M. T. Awwad, I. I. Ikhries, Z. S. Abu-Hamatteh, and N. A. Al-Najdawi, "Assessing recycled polyvinyl chloride reinforced modified asphalt mixtures for sustainable paving applications," *Journal of Cleaner Production*, vol. 486, 2025, doi: 10.1016/j.jclepro.2024.144583.
[22] A. R. Ghanizadeh, F. S. Jahanshahi, V. Khalifeh, and F. Jalali, "Predicting flow number of asphalt mixtures based on the marshall mix design parameters using multivariate adaptive regression spline (mars)," *International Journal of Transportation Engineering (IJTE)*, vol. 7, no. 4, pp. 433-448, 2020, doi: 10.22119/IJTE.2020.184115.1476.
[23] M. Zarei, M. R. Taghizadeh, S. S. Moayedi, A. Naseri, M. Al-Bahrani, and M. W. Khordehbinan, "Evaluation of fracture behavior of warm mix asphalt (wma) modified with hospital waste pyrolysis carbon black (hwpcb) under freeze–thaw damage (ftd) at low and intermediate temperatures," *Construction and Building Materials*, vol. 356, 2022, doi: 10.1016/j.conbuildmat.2022.129184.
[24] F. Xu, Y. Zhao, and K. Li, "Using waste plastics as asphalt modifier: a review," *Materials*, vol. 15, no. 1, p. 110, Dec. 2021, doi: 10.3390/ma15010110.
[25] F. Rondinella, C. Oreto, F. Abbondati, and N. Baldo, "Laboratory investigation and machine learning modeling of road pavement asphalt mixtures prepared with construction and demolition waste and rap," *Sustainability (Switzerland)*, vol. 15, no. 23, 2023, doi: 10.3390/su152316337.
[26] X. Zhong, B. Gallagher, S. Liu, B. Kailkhura, A. Hiszpanski, and T. Y.-J. Han, "Explainable machine learning in materials science," *npj Computational Materials*, vol. 8, no. 1, pp. 1-19, Sep. 2022, doi: 10.1038/s41524-022-00884-7.
[27] A. H. Albayati, Y. S. Jweihan, and M. J. Al-Kheetan, "Utilizing soft computing techniques to estimate the axial permanent deformation of asphalt concrete," *Applied System Innovation*, vol. 8, no. 2, pp. 1-16, Feb. 2025, doi: 10.3390/asi8020026.
[28] A. Upadhya, M. S. Thakur, A. Mashat, G. Gupta, and M. S. Abdo, "Prediction of binder content in glass fiber reinforced asphalt mix using machine learning techniques," *IEEE Access*, vol. 10, pp. 33866–33881, 2022, doi: 10.1109/ACCESS.2022.3157639.
[29] M. Arifuzzaman, H. J. Qureshi, A. F. Al Fuhaid, F. Alanazi, M. F. Javed, and S. M. Eldin, "Novel ensemble modelling for prediction of fundamental properties of bitumen incorporating plastic waste," *Journal of Materials Research and Technology*, vol. 24, pp. 3334–3351, 2023, doi: 10.1016/j.jmrt.2023.03.218.
[30] B. Kumar, N. Kumar, R. Rustum, and V. Shankar, "Comparative analysis of machine learning techniques for predicting bulk specific gravity in modified asphalt mixtures incorporating polyethylene terephthalate (PET), high-density polyethylene (HDPE), and polyvinyl chloride (PVC)," *Machine Learning and Knowledge Extraction*, vol. 7, no. 2, 2025, doi: 10.3390/make7020030.
[31] Y. Yan, L. Ni, L. Sun, Y. Wang, and J. Zhou, "Digital twin enabling technologies for advancing road engineering and lifecycle applications," *Engineering*, vol. 44, pp. 184–206, Jan. 2025, doi: 10.1016/j.eng.2024.12.017.
[32] S. Salehi, M. Arashpour, E. Mohammadi Golafshani, and J. Kodikara, "Prediction of rheological properties and ageing performance of recycled plastic modified bitumen using machine learning models," *Construction and Building Materials*, vol. 401, pp. 1-15, Oct. 2023, doi: 10.1016/j.conbuildmat.2023.132728.
[33] Eche Samuel Okem, Tosin Daniel Iluyomade, and Dorcas Oluwajuwonlo Akande, "Revolutionizing u.s. pavement infrastructure: a pathway to sustainability and resilience through nanotechnology and ai innovations," *World Journal of Advanced Engineering Technology and Sciences*, vol. 11, no. 2, pp. 411–428, Apr. 2024, doi: 10.30574/wjaets.2024.11.2.0124.
[34] V. Gupta *et al.*, "MPpredictor: an artificial intelligence-driven web tool for composition-based material property prediction," *Journal of Chemical Information and Modeling*, vol. 63, no. 7, pp. 1865–1871, 2023, doi: 10.1021/acs.jcim.3c00307.
[35] M. J. Page *et al.*, "The prisma 2020 statement: an updated guideline for reporting systematic reviews," *BMJ*, vol. 372, no. 71. p. n71, Mar. 29, 2021, doi: 10.1136/bmj.n71.
[36] A. P. Siddaway, A. M. Wood, and L. V Hedges, "How to do a systematic review: a best practice guide for conducting and reporting narrative reviews, meta-analyses, and meta-syntheses," *Annual Review of Psychology*, vol. 70, no. 1, pp. 747–770, Jan. 2019, doi: 10.1146/annurev-psych-010418-102803.
[37] D. Moher *et al.*, "Preferred reporting items for systematic review and meta-analysis protocols (prisma-p) 2015 statement," *Revista Espanola de Nutricion Humana y Dietetica*, vol. 20, no. 2, pp. 148–160, 2016, doi: 10.1186/2046-4053-4-1.
[38] K. Kolaski, L. R. Logan, and J. P. A. Ioannidis, "Guidance to best tools and practices for systematic reviews," *JBI Evidence Synthesis*, vol. 21, no. 9, pp. 1699–1731, Sep. 2023, doi: 10.11124/JBIES-23-00139.
[39] R. Negarandeh and R. Beykmirza, "Quality assessment in systematic reviews: the importance of choosing the right tools," *Nursing Practice Today*, vol. 7, no. 3, pp. 161–162, Jun. 2020, doi: 10.18502/npt.v7i3.3342.
[40] A. Liberati *et al.*, "The prisma statement for reporting systematic reviews and meta-analyses of studies that evaluate health care interventions: explanation and elaboration," *Journal of Clinical Epidemiology*, vol. 62, no. 10, pp. e1–e34, Oct. 2009, doi: 10.1016/j.jclinepi.2009.06.006.
[41] B. Cui and H. Wang, "Compatibility analysis of waste polymer recycling in asphalt binder using molecular descriptor and graph neural network," *Resources, Conservation and Recycling*, vol. 212, pp. 1-9, Jan. 2025, doi: 10.1016/j.resconrec.2024.107950.
[42] U. Asif, M. F. Javed, D. M. Alsekait, D. S. AbdElminaam, and H. Alabduljabbar, "Toward sustainability: integrating experimental study and data-driven modeling for eco-friendly paver blocks containing plastic waste," *Reviews on Advanced Materials Science*, vol. 63, no. 1, 2024, doi: 10.1515/rams-2024-0051.
[43] A. Sharma, P. K. Singh, E. Makki, J. Giri, and T. Sathish, "A comprehensive review of critical analysis of biodegradable waste pcm for thermal energy storage systems using machine learning and deep learning to predict dynamic behavior," *Heliyon*, vol. 10,

no. 3, pp. 1-25, Feb. 2024, doi: 10.1016/j.heliyon.2024.e25800.
[44] H. Gardezi *et al.*, "Predictive modeling of rutting depth in modified asphalt mixes using gene-expression programming (gep): a sustainable use of rap, fly ash, and plastic waste," *Construction and Building Materials*, vol. 443, 2024, doi: 10.1016/j.conbuildmat.2024.137809.
[45] M. Junaid, C. Jiang, U. Gazder, I. Hafeez, and D. Khan, "Evaluation of asphalt mixtures modified with low-density polyethylene and high-density polyethylene using experimental results and machine learning models," *Scientific Reports*, vol. 14, no. 1, pp. 1-14, 2024, doi: 10.1038/s41598-024-74657-1.
[46] B. Iftikhar *et al.*, "A machine learning-based genetic programming approach for the sustainable production of plastic sand paver blocks," *Journal of Materials Research and Technology*, vol. 25, pp. 5705–5719, 2023, doi: 10.1016/j.jmrt.2023.07.034.
[47] C. Vargas and A. El Hanandeh, "Features importance and their impacts on the properties of asphalt mixture modified with plastic waste: a machine learning modeling approach," *International Journal of Pavement Research and Technology*, vol. 16, no. 6, pp. 1555–1582, 2023, doi: 10.1007/s42947-022-00213-7.
[48] A. Upadhya *et al.*, "Modelling and prediction of binder content using latest intelligent machine learning algorithms in carbon fiber reinforced asphalt concrete," *Alexandria Engineering Journal*, vol. 65, pp. 131–149, 2023, doi: 10.1016/j.aej.2022.09.055.
[49] Y. Song, Y. D. Wang, X. Hu, and J. Liu, "An efficient and explainable ensemble learning model for asphalt pavement condition prediction based on ltpp dataset," *IEEE Transactions on Intelligent Transportation Systems*, vol. 23, no. 11, pp. 22084–22093, Nov. 2022, doi: 10.1109/TITS.2022.3164596.
[50] H. Li *et al.*, "Analysis of the influence of production method, plastic content on the basic performance of waste plastic modified asphalt," *Polymers*, vol. 14, no. 20, pp. 1-19, 2022, doi: 10.3390/polym14204350.

BIOGRAPHIES OF AUTHORS

I Gusti Agung Ananda Putra received his Bachelor's degree in Civil Engineering from the University of Udayana, Bali, in 2016, and his Master's degree in Civil Engineering from the same institution in 2018. He completed his Doctorate in Engineering, specializing in Civil Engineering, at the University of Udayana in 2024, graduating cum laude. Currently, he is the Head of the Environmental Engineering Study Program at the Faculty of Engineering and Informatics, Universitas Pendidikan Nasional (Undiknas), Denpasar, Bali. His research interests include waste management, sustainable construction materials, and environmental technology. He can be contacted at email: anandaputra@undiknas.ac.id.

Darpan Rokade received his Bachelor's degree in Computer Science from P.E.S. Modern College of Arts, Science and Commerce, Ganeshkhind, Pune, India. His research interests include artificial intelligence, machine learning, and cognitive computing applications in education and healthcare. He can be contacted at email: darpanrokade5@gmail.com.