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Review Article

A Systematic Literature Review of Machine Learning, Deep Learning, and Explainable AI for Predicting Mechanical Performance and Microplastic Release in Plastic Waste-Modified Asphalt

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Abstract *- The growing pile of plastic waste has led to the implementation of sustainable engineering solutions, such as putting recycled plastics into asphalt mixtures, referred to as Plastic Waste-Modified Asphalt (PWMA). Despite the fact that in earlier studies, a significant improvement in mechanical performance, particularly stiffness and rutting resistance, has been demonstrated, there has been no emphasis on the environmental consequences related to it, particularly microplastic release (MPs). In line with this, Machine Learning (ML) and Deep Learning (DL) models have been highly used in estimating the performance of pavement with a high level of accuracy, but their non-conventional characteristics make them hard to implement in the engineering profession. It is a systematic literature review that is based on PRISMA 2020 and aims to summarize the most up-to-date state-of-the-art in the crossroads of PWMA, advanced computational modeling, and environmental sustainability. 36 peer-reviewed articles that were published in 2019-2026 were examined. The results indicate that the DL models (particularly Multi-Layer Perceptron (MLP) and Neural Architecture Search-based models) have high predictive accuracy ($R^2 > 0.95$), which is higher than the traditional ML methods. However, 32 of the 36 reviewed studies (88.9%) primarily focused on mechanical performance, whereas only 4 studies (11.1%) addressed microplastic-related environmental issues. In addition, there is an explainability gap, with only 4 of the 36 studies (11.1%) incorporating Explainable Artificial Intelligence (XAI) methods. A suspected trade-off that is of critical importance in this paper is the possibility of a higher content of plastics to result in a higher stiffness but potentially higher rates of microplastic formation due to the brittle nature of materials. To overcome these shortcomings, a new Explainable Deep Learning (XDL) architecture is suggested that allows predicting mechanical performance and microplastic emissions simultaneously with greater interpretability. The specified strategy will be used to develop data-driven, transparent, and sustainable pavement design strategies.*

Keywords *- Plastic Waste-Modified Asphalt, Microplastic release, Machine Learning, Deep Learning, Explainable Artificial Intelligence.*

1. Introduction

The rapid growth in terms of producing and using plastics has led to a huge ecological disaster in which plastic waste has accumulated in the land and water bodies because of its non-biodegradability and a weak waste management system [1, 2]. This is an increasing issue that has contributed to the transition to the use of a circular economy in which waste products are re-engineered into engineering applications [3-5]. Plastic Waste-Modified Asphalt (PWMA) is one of the solutions that have potential in the context of pavement engineering, which can not only resolve the problem of environmental concerns but also infrastructural issues [6, 7]. Several authors have demonstrated that Polyethylene Terephthalate (PET), High-Density Polyethylene (HDPE), and Polyvinyl Chloride (PVC) thermoplastic asphalt mixtures can significantly enhance the mechanical behavior of asphalt mixtures, which means that they have better rutting resistance, stiffness, and longevity [8, 9].

Alongside the development of new material, the application of state-of-the-art computational techniques has transformed the pavement performance evaluation and prediction as well. Deep Learning (DL) models and Machine Learning (ML) models, including Artificial Neural Networks (ANN), Multi-Layer Perceptron (MLP), and similar ensemble models, like Extreme Gradient Boosting (XGBoost) have demonstrated excellent predictive capabilities in estimating such fundamental mechanical properties as Marshall Stability, dynamic modulus, and fatigue life [10]. These models have been especially useful in modeling the very complicated, nonlinear relationships that exist between the variables of mixture design and their performance results, frequently with Coefficients of Determination (R^2) of more than 0.95. Despite such innovations, most of the existing models have been developed as black-box models, which do not provide much information on the contribution of the input variables, such as plastic dosage, mixing temperature, and binder composition to the responses predicted [11, 12].

Despite the fact that the mechanical benefits of PWMA are highly reported, a considerable gap in literature on environmental impacts of the technology exists. Specifically, the possibility of the release of microplastics (MPs) that are produced as a result of traffic abrasion, thermal and environmental weathering of plastic-modernized pavements has been relatively under-researched. Recent studies have shown that processes of surface degradation can also lead to the formation of microplastic particles, which can be transported to other ecosystems through runoff channels [13, 14]. But in contrast to mechanical performance, which has been extensively simulated with the help of both ML and DL models, the quantitative prediction of microplastic release is not well developed yet and is mostly empirical. This gap indicates a knowledge gap between structural optimization and environmentally friendly systems in PWMA systems [14, 15]. Furthermore, the fact that contemporary predictive models cannot be interpreted adds to this gap. The black-box characteristics of most ML/DL methods restrict their use in engineering decision-making, where the causal relationship is needed to risk assessment and material design [16, 17]. Recently, explainable Artificial Intelligence (XAI) methods, including Shapley Additive Explanations (SHAP) and Local Interpretable Model-Agnostic Explanations (LIME), have become effective to improve transparency of models by measuring the impact of single input features on model predictions [18, 19]. However, they are still rarely used in PWMA research, particularly in those research studies which seek to simultaneously determine mechanical performance and environmental emissions.

Given these challenges, several critical research questions arise: how accurately can ML and DL models predict the mechanical performance of plastic-modified asphalt mixtures across varying material compositions? To what extent have existing studies succeeded in quantifying and predicting microplastic release from pavement systems? And how can the integration of XAI techniques improve the interpretability of predictive models while bridging the gap between structural performance and environmental impact? Addressing these questions is essential for advancing the development of sustainable pavement technologies that are both high-performing and environmentally responsible.

Therefore, this study aims to present a comprehensive and methodical survey of the state of the art at the crossroad of PWMA, sophisticated modeling and environmental sustainability [20, 21]. In particular, this article adds value by (i) introducing the first coherent systematic literature review that concomitantly studies mechanical performance prediction and microplastic emission in PWMA with ML/DL methods, (ii) elucidating and critically discussing the current so-called explainability gap in predictive pavement modeling, (iii) quantitative synthesis of model behavior across various computational architectures, and (iv) a new Explainable Deep Learning (XDL) framework that allows the simultaneous prediction of structural integrity and microplastic release with greater interpretability. The proposed research should be used to help advance the future of decision-support systems in sustainable pavement engineering by closing the predictive accuracy versus physical understanding gap.

Plastic Waste-Modified Asphalt (PWMA) offers a promising approach to waste valorization and pavement performance improvement, but existing studies predominantly focus on mechanical properties, while potential microplastic release and environmental consequences remain comparatively underexplored. Although Machine Learning (ML) and Deep Learning (DL) can model complex relationships among plastic type, dosage, processing conditions, and pavement performance, many existing models provide limited interpretability and rarely integrate mechanical and environmental outcomes within a common framework. This review therefore addresses three key gaps: the limited integration of mechanical performance and microplastic-release assessment, insufficient interpretability of predictive models, and the lack of a unified framework connecting material characteristics, pavement performance, environmental outcomes, and Explainable Artificial Intelligence (XAI). Using a PRISMA-based systematic review, the study compares conventional modeling, ML, DL, and XAI approaches and evaluates datasets, validation strategies, predictive metrics, and research trends. Based on the identified gaps, a conceptual Explainable Deep Learning (XDL) framework is proposed as a future research direction for developing more transparent, integrated, and environmentally informed prediction of PWMA performance and potential microplastic release.

Research on asphalt modified with plastic waste is expanding, yet significant limitations persist. Current investigations primarily concentrate on mechanical properties, with considerably less focus on the environmental consequences of microplastics. Furthermore, while machine-learning and deep-learning techniques show potential for prediction, variations in data, objectives, validation methods, and performance measures impede direct comparisons between studies. Lastly, the infrequent use of explainability methods hinders comprehension of how material characteristics and production factors affect model outcomes.

Most importantly, the available literature does not yet provide a validated and integrated framework that jointly considers mechanical performance, microplastic-related environmental outcomes, and model interpretability. Accordingly, this study aims to provide a systematic and critical synthesis of research at the intersection of PWMA, advanced computational modeling, and environmental sustainability.

The review addresses four objectives: (i) to map the material, modeling, and environmental themes represented in the selected literature; (ii) to compare reported ML and DL applications while considering validation rigor and interpretability; (iii) to examine the imbalance between mechanical and microplastic-related research; and (iv) to identify the methodological requirements for future multi-output and explainable predictive frameworks.

The novelty of this review does not lie in the experimental validation of a new predictive model. Rather, it lies in the systematic integration of evidence on mechanical performance, microplastic-related environmental concerns, and explainable artificial intelligence, followed by the formulation of an Explainable Deep Learning research framework as a future direction.

2. Literature Review

2.1. Utilization of Recycled Plastics in Asphalt Mixtures

As a sustainable method of using the recycled plastics, it is then incorporated into asphalt mixtures to enhance the material performance, as well as the environmental issues [22-24]. Thermoplastic polymers that have been widely investigated as modifiers include PET, HDPE, LDPE and PVC since they can be incorporated to enhance the viscoelastic characteristics of bituminous binders [25], [26]. These materials increase stiffness, rutting resistance and durability particularly at high-temperature environment operation [27-29].

In material engineering terms, plastic modification is very sensitive to a number of factors, such as the type of polymer, particle size, method of blending (wet process vs. dry process), and dosage. The study indicates that maximum dosage levels are always attained which produce the best results (generally 5-15% beyond which the negative effects like brittleness and fatigue resistance may be encountered) [9]. This means that PWMA behavior is nonlinear and is a function of parameters of the mixture design and thus difficult to model on the basis of traditional empirical approaches.

In spite of these advantages, even the majority of studies are centered on such mechanical performance measures and hardly pay attention to long-term environmental implication. This narrowness does not allow considering the sustainability of PWMA systems as a whole, in particular, in terms of the lifecycle impact and degradation processes.

2.2. Conventional and Experimental Approaches for PWMA Performance

Before the adoption of machine learning and deep learning, the performance of Plastic Waste-Modified Asphalt (PWMA) was primarily evaluated through laboratory experiments and conventional empirical approaches. Marshall stability, flow, stiffness, rutting resistance, fatigue behavior, moisture susceptibility, and durability tests have been widely used to assess the effects of plastic type, dosage, particle characteristics, and mixing conditions on asphalt performance. Experimental approaches remain important because they provide direct measurements of material behavior and establish the physical evidence required for developing predictive models.

However, laboratory-based approaches can be resource-intensive and generally evaluate a limited range of material and environmental conditions. Conventional statistical and empirical models can provide useful relationships between input variables and pavement responses, but their ability to represent highly nonlinear interactions may be limited. These limitations have encouraged the increasing application of machine learning and deep learning techniques for PWMA prediction. Nevertheless, experimental and conventional approaches remain essential because they provide the physical basis against which data-driven models should be validated.

2.3. Microplastic Release and Environmental Concerns

Recently studies have started pointing out the environmental hazards presented by plastic-modified asphalt, and specifically the release of Microplastics (MPs) as a result of mechanical and environmental degradation [29, 30]. Surface wear occurs due to traffic loading, tire-pavement contact, Ultraviolet (UV) radiation and thermal aging and may lead to shedding of micro-scale plastic particles of the pavement matrix [31, 32].

Though the existence of microplastics in road environments is not a recent discovery, most available literature is not based on predictive modelling but on laboratory observations or post-evental environmental sampling [33, 34]. This leaves a big gap in the capability to predict microplastic emissions in different operating conditions. Furthermore, recent research is inclined to discuss the release of microplastics as an isolated environmental issue, and does not directly relate its material properties (stiffness, brittleness, or binder structure) to it [35, 36]. This is systems problematic disconnection. Unwilling surface fragmentation, which can be hastened by mechanical enhancements, such as greater stiffness, using more plastic material, thereby, enhancing the risk of microplastic release. Nonetheless, this trade-off has not been studied in a quantitative manner yet, and it is important to note that quantitative studies should be integrated into modeling techniques that can be used in parallel to think about structural performance and environmental emissions [37, 38].

Environmental assessment of PWMA should extend beyond mechanical performance to include material degradation, microplastic release, resource consumption, and end-of-life implications. Life Cycle Assessment (LCA) provides a broader framework for evaluating environmental impacts throughout the material and pavement life cycle, including production, transportation, construction, service, maintenance, and disposal or recycling stages.

In the context of PWMA, LCA can therefore complement mechanical testing by identifying whether the environmental benefits associated with plastic waste diversion are maintained when material production, pavement performance, degradation, and end-of-life processes are considered. However, LCA-based assessment and experimental microplastic investigations are generally not integrated with predictive ML/DL models, leaving an important methodological gap between environmental assessment and data-driven pavement performance prediction

2.4. Application of Machine Learning and Deep Learning in Pavement Engineering

Asphalt materials are a species of complex behavior, and this has resulted in adopting the concepts of the Machine Learning (ML) and Deep Learning (DL) technologies as alternatives to the previous empirically and mechanistically based models. Nonlinear interactions between input parameters (e.g., binder composition, temperature, loading conditions) and experimental results (e.g., rutting depth, dynamic modulus, fatigue life) can be modelled using such data-based modelling techniques.

RF and XGBoost are ensemble methods of learning, which have demonstrated excellent performance in predicting the mechanical properties using structured laboratory data. Concurrently, Deep Learning structures, including Artificial Neural Networks (ANN), Multi-Layer Perceptron (MLP) and Neural Architecture Search-based models ANN(NAS-ANN), have proven to be more accurate in predictive performance, particularly in highly rheological properties [39, 40].

Although they are very accurate, these models can be criticized due to their uninterpretability [41, 42]. The black-box character of DL models restricts their usefulness in engineering settings, where the impact of single parameters is crucial in optimizing the design and mitigating risk. This has given rise to a desire to come up with model methods that are predictive yet interpretable.

2.5. Explainable Artificial Intelligence (XAI) in Material Modeling

Explainable Artificial Intelligence (XAI) has become a potential solution to the interpretability issues with advanced ML and DL models. Other techniques such as SHapley Additive ExPlanation (SHAP), Partial Dependence Plots (PDP), and Local Interpretable Model-Agnostic Explanations (LIME) enable the researchers measure the influence of discrete input features on model predictions [2, 43].

Applied to pavement engineering, XAI offers useful information on the multifaceted interactions between the parameters of a mixture design and the performance results [28, 44]. As an example, SHAP analysis can be applied to demonstrate that mixing temperature can influence performance more than plastic dosage or demonstrate the impact of a specific combination of variables on performance. The knowledge is essential towards transforming data-driven predictions into feasible engineering choices.

However, the application of XAI in PWMA research is not common. Most research does not use interpretability techniques or does so in a shallow fashion, only considering feature importance without considering in-depth interactions [34, 45]. Better said, there is a lack of literature regarding the use of XAI to elucidate the mechanical performance as well as environmental performance, i.e. microplastic release.

2.6. Synthesis of Research Gaps and the Need for XDL Integration

Critical analysis of the available literature depicts that there are three broad gaps. Firstly, there is a ridiculously skewed number of studies that examine mechanical performance and the number of studies that examine environmental impact are much less openly examined. Second, both the ML and DL model have demonstrated high predictive performance, but the fact that they cannot be interpreted limits their application to engineering design and policy-making. Third, no models are available which would simultaneously model mechanical behavior and microplastic emissions.

These shortcomings imply the necessity of new modeling paradigm that combines predictive nature of Deep Learning and the interpretability of XAI. All of these approaches together, which in this publication are referred to as Explainable Deep Learning (XDL), may offer a valuable point of departure into bridging the gap between the optimization of structures and environmental sustainability. XDL has the potential to improve more informed and sustainable decision-making in pavement engineering since it enables simultaneous prediction and interpretation of mechanical and environmental outputs.

The keyword co-occurrence network created with VOS-viewer is provided in Figure 1. In the field of Plastic Waste-Modified Asphalt (PWMA), there are evident clusters of research as depicted in the visualization. The red cluster dwells mainly on the core material elements, such as plastic, asphalt, asphalt mixture, and mechanical performance meaning that most of the studies accentuate structural performance assessment. The green cluster is connected with the performance-related parameters, the ones, such as rutting, resistance, and performance, demonstrating a significant concentration on the durability and deformation behavior. Meanwhile, the blue cluster attracts the attention to such terms like waste plastic, suggesting the aspect of sustainability and recycling of the field of the research.

However, despite these strong clusters, the network itself does not exhibit any profound connections between environmental keywords (e.g., microplastic-related keywords) and sophisticated computational procedures (e.g., machine learning or explainable AI). This shows there is a disjoint in the existing research area, in which mechanical performance, environmental impact and data-driven modeling are examined as isolated concepts, as opposed to them being integrated to study each other. This is also one of the reasons that prove the gap in the research that the current study has identified and why an integrated Explainable Deep Learning (XDL) framework is supposed to be created.

In Figure 1 we can see three research clusters dominating. The core and mechanical performance material is the red cluster and implies that the majority of the studies are concerned with the structural behavior, such as stiffness, and rutting resistance. The green cluster can be considered as a reflection of performance parameters with durability-related investigations in the lead. In the meantime, the blue cluster explains the themes of sustainability, in particular, the waste plastic application.

However, a skeptical commentary comes in considerations of the network structure: the keywords of environmental concern, in particular, the release of microplastic, are not strongly tied to the keywords of computational modeling such as machine learning and explainable AI. This discontinuity implies that the area of mechanical performance, environmental impact, and data-driven modeling is mostly explored independently of each other, as opposed to an integrated framework [46, 47]. This gap directly justifies the main research gap of this study and highlights the need to have an integrated Explainable Deep Learning (XDL) approach.

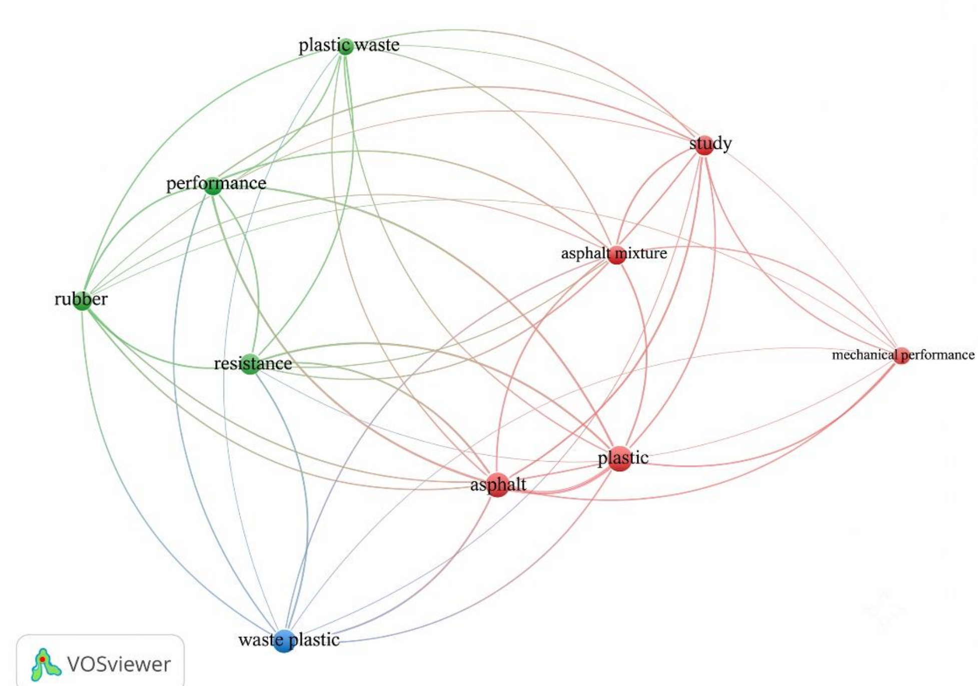

Fig. 1 VOS-viewer analysis

3. Methods

3.1. Research Design and Review Framework

To ensure methodological rigour, transparency and reproducibility when synthesizing the current body of knowledge regarding plastic waste-modified asphalt (PWMA), the approach of a Systematic Literature Review (SLR) was conducted in this study following the PRISMA 2020 (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines that offer a systematic pattern of recognizing, screening, and choosing the pertinent studies.

The general flow of the review process is depicted in Figure 2 (PRISMA 2020 Flow Diagram for Study Selection) and displays the consecutive steps of literature identification, screening, eligibility check, and ultimate inclusion. This is a systematic method, which will mean that the selection procedure will be transparent and reduce possible bias in including the studies. Figure 2 presents a very orderly and organized study selection process, including identification, screening, eligibility and inclusion. This method can be used to guarantee methodological rigor, and limit selection bias.

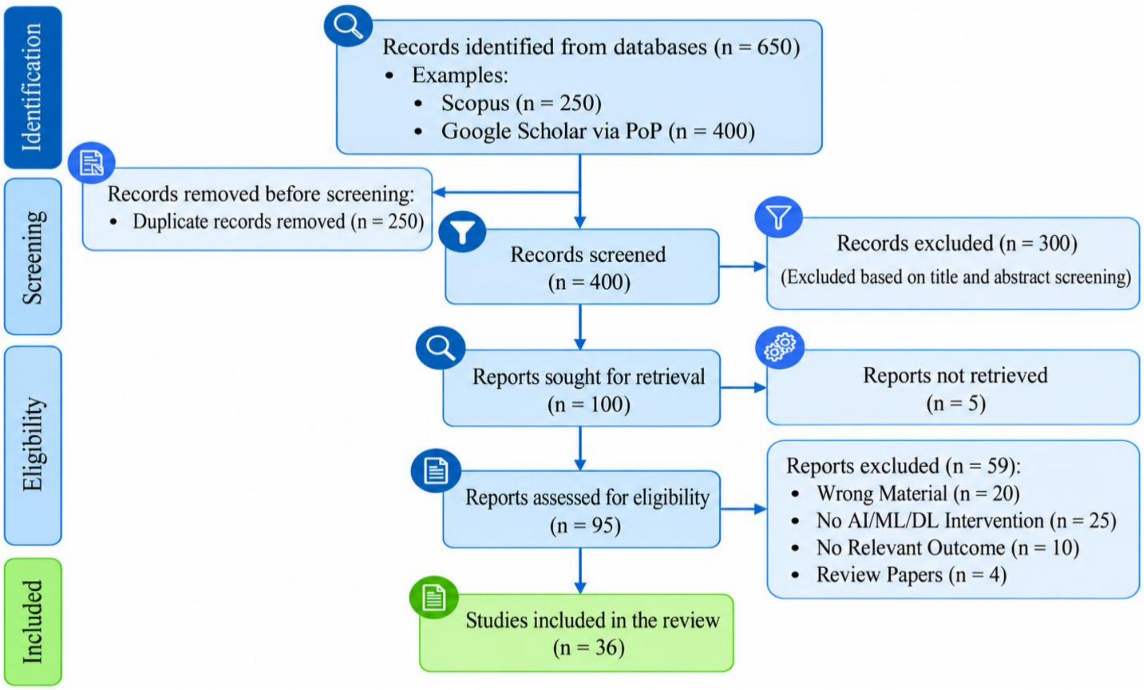

Fig. 2 PRISMA 2020 flow diagram for study selection (PWMA & XDL)

3.2. Search Strategy and Data Sources

An extensive literature review was performed in key scientific databases, such as Scopus, Web of Science, and Google Scholar to identify high-impact and peer-reviewed articles concerning the goals of the research. Publish or Perish software was employed in enhancing the rate and stability of metadata extraction.

The search strategy was developed based on Boolean operators in order to obtain the intersection of three main areas, namely: (i) plastic-modified asphalt, (ii) mechanical and environmental performance, and (iii) advanced computational modeling. The search query that was applied in this study is as follows:

("plastic modified asphalt" OR "plastic waste asphalt" OR "recycled plastic pavement")
AND ("microplastic" OR "mechanical performance" OR "rutting")
AND ("deep learning" OR "explainable AI" OR "XAI" OR "machine learning")

To ensure that the review itself covers the latest innovations in the sphere of pavement engineering along with the use of artificial intelligence, the timeframe of the search was considered to be 2019 to 2026.

3.3. Eligibility Criteria (Domain-Adapted PICOS Framework)

To ensure that the selected studies were relevant and consistent with the objectives of this engineering and computational review, the inclusion and exclusion criteria were developed using a domain-adapted PICOS (Population/Problem, Intervention/Approach, Comparison, Outcome, and Study Design) framework, as presented in Table 1. The framework was adapted to reflect the multidisciplinary characteristics of plastic waste-modified asphalt, pavement engineering, and data-driven predictive modeling.

Table 1. Inclusion and exclusion criteria based on PICO framework

Criteria	Inclusion	Exclusion
Population	Asphalt mixtures incorporating recycled plastic materials (PET, HDPE, LDPE, PVC)	Conventional asphalt, rubber-only modification
Intervention	ML, DL, or XAI-based predictive modeling	Purely experimental or statistical without predictive modeling
Comparison	Conventional asphalt, alternative plastic contents, or alternative predictive models	Studies without a relevant comparison or benchmark.
Outcome	Mechanical performance and/or microplastic release	Economic or policy-only studies
Study Type	Articles published in peer-reviewed journals	Conference proceedings, review articles, and book chapters

Table 1 ensures that the selected studies are closely aligned with the objectives of the review, particularly the integration of material engineering, pavement performance, environmental considerations, and predictive modeling. The domain-adapted PICOS framework provides a transparent and reproducible basis for screening studies while maintaining the multidisciplinary scope of the review.

3.4. Screening Process and Study Selection

The first query resulted in a total of n = 650 records. Once the duplicates were eliminated, there were n = 250 unique studies that were screened. The selection was done in two phases:

a. Title and Abstract Screening: Studies were evaluated based on their relevance to the research objectives using predefined PICO criteria.
b. Full-Text Review: Selected articles were further assessed for methodological completeness, availability of model performance metrics, and relevance to PWMA.

Screening was carried out in the Rayyan intelligent systematic review platform, which allows conducting a blind screening to decrease the selection bias. The end result is 36 high-quality studies as shown in Figure 2 (PRISMA Flow Diagram).

3.5. Quality Assessment and Risk of Bias Analysis

A quality evaluation of the chosen studies was done to be sure that the synthesized results are reliable and robust. The next criteria were used to rate all the studies:

a. Dataset size and representativeness
b. Model validation approach (e.g., cross-validation, train-test split)
c. Reporting of performance metrics (R^2, RMSE, MAE)
d. Risk of overfitting
e. Transparency of methodology

Each criterion had a score on a scale of 1 (low) to 3 (high) and provided a cumulative quality score to each study. The quality of the methodology and the risk of bias of the chosen studies will be assessed in Table 2.

Most of the studies depict a moderate to high quality of the methodology as illustrated in Table 2, particularly, the performance reporting and validation methods. However, there are several weaknesses that are evident. Many of the research works use medium-sized datasets and an uncomplicated train-test split which can lead to overfitting as well as restrict the applicability of the model. In addition, not many studies combine transparency-enhancing strategies such as SHAP and, therefore, interpretability is not well-established. This finding justifies the need to include explainable AI in predictive modeling systems.

3.6. Data Extraction and Coding Framework

To obtain the variables of each of the identified studies in a systematic fashion, a systematic data collection procedure was developed. Table 3 gives a systematic outline of the selected researches and the model of the method employed.

The parameters obtained are:

a. Study metadata (author, year)
b. Type of plastic modifier and dosage (%)
c. Type of ML/DL/XAI model
d. Input variables (e.g., temperature, binder composition)
e. Output variables (mechanical and/or environmental)
f. Performance metrics (R^2, RMSE, MAE)

Table 2. Quality assessment and risk of bias evaluation of selected studies

Study	Data Size	Validation Method	Metrics	Transparency	Score
Sadoudi et al. (2025) [10]	Large	Cross-validation	R^2, RMSE	High (Hybrid AI)	14
Kumar and Kumar (2024) [34]	Medium	Train-test split	R^2, MAE	Medium	12
Gardezi et al. (2024) [37]	Small	Limited validation	R^2	Low	9
Haider et al. (2024) [45]	Medium	Cross-validation	R^2, RMSE	Medium	12
Mohammadi and Ameri (2024) [38]	Review	Not applicable	—	High	13

Table 3. Summary of selected studies and modeling approaches

Author	Plastic Type	Model	Input	Output	Performance
Gardezi et al. (2024) [37]	Mixed + RAP	GEP	Mix design	Rutting depth	High accuracy
Sadoudi et al. (2025) [10]	Modified bitumen	Hybrid AI	Penetration, softening point	Mechanical properties	$R^2 > 0.95$
Kumar and Kumar (2024) [34]	Waste plastic	ANN/SVM	Mix parameters	Marshall Stability	$R^2 \approx 0.96$
Haider et al. (2024) [45]	Waste plastic modifiers	GEP	Moisture variables	Moisture damage indices	High accuracy

Table 3 highlights PWMA studies using various modeling techniques and combinations of materials. Even though various machine learning and deep learning models have already been successfully applied, most of the studies focus on mechanical performance, such as rutting resistance and stability. It is also important to note that the table shows that relatively few studies use interpretability techniques (e.g., SHAP), and none of the reviewed studies explicitly models microplastic release. This supports the presence of a research gap at the intersection of predictive modeling and environmental sustainability. The reviewed literature is predominantly focused on mechanical performance prediction, particularly Marshall stability, rutting resistance, and stiffness, whereas environmental considerations are less frequently addressed and are mainly associated with qualitative assessments or life-cycle studies rather than predictive modeling.

In addition, machine learning and deep learning techniques have become increasingly prevalent in recent years; however, the use of explainable artificial intelligence (XAI) remains limited. SHAP-based approaches appear only in a small number of studies, indicating that model interpretability has not yet been widely examined. More importantly, none of the reviewed studies explicitly develops a quantitative predictive model for microplastic release, highlighting a fundamental gap between mechanical optimization and environmental impact assessment.

A data extraction matrix was developed to systematically record the parameters reported in the 36 included studies. The extracted variables included author metadata, polymer type and dosage, additional modifiers, primary AI/DL architecture (e.g., MLP, XGBoost, CNN), XAI methods (e.g., SHAP, PDP), key input features, target mechanical and environmental outputs, and reported predictive performance metrics.

3.7. Data Synthesis and Analytical Approach

Data were extracted using a mixed-method synthesis that interprets the data between a qualitative narrative analysis, and a quantitative comparison. A descriptive analysis was initially used to identify the research trends (e.g., the distribution of studies by the year of publication, plastic type e.g. PET, HDPE or modeling method e.g. ML, DL, XAI). The move provides us with a clue about the evolution of PWMA research and the increasing tendency towards the use of data-driven approaches.

Subsequently, the key performance measures such as R^2, RMSE and MAE were used to conduct a quantitative and comparative analysis to determine the accuracy of the model. Moreover, the gap analysis was done to identify gaps in the literature, particularly, in the sphere of mechanical performance and environmental assessment, and absence of XAI use. These results are generalized, and it is where the idea of proposing an integrated Explainable Deep Learning (XDL) framework is based.

3.8. Bias Mitigation and Limitations

There are a few limitations to this study. Firstly, the peer-reviewed journal articles that are incorporated in the review limit themselves to the years 2019-2026 and the English language, which may lead to publication bias and language bias. Second, the selected papers are extremely diverse regarding the size of the datasets, material properties and modeling techniques, which limit their direct comparability.

In addition, the vast majority of studies rely on quite small datasets and an uncomplicated validation procedure, which may call the relevance of the model and even the risk of overfitting into question. Lastly, the scanty literature on the prediction of microplastic and the unequal use of XAI techniques limits the intensiveness of environmental and explainability examination. These restrictions indicate that the further studies should use more unified and standardized research.

4. Results and Discussion

4.1. Study Selection and General Characteristics

This methodical screening procedure resulted in the ultimate list of 36 peer-reviewed articles as indicated in Figure 2 (PRISMA 2020 Flow Diagram for Study Selection). The number of studies increases significantly after 2022, as Figure 3 (Publication Trend of PWMA Research 2019 2026) indicates, which can be attributed to the fact that the interest in using sustainable materials in advanced methods of computation is growing. Even though, as Figure 3 shows, the research activity has been increasing at a steep rate since 2022, it seems that a new wave of enthusiasm toward the use of sustainable materials and the newest computational methods is approaching. The trend is similar to the global trend towards the circular economy and smart infrastructure systems.

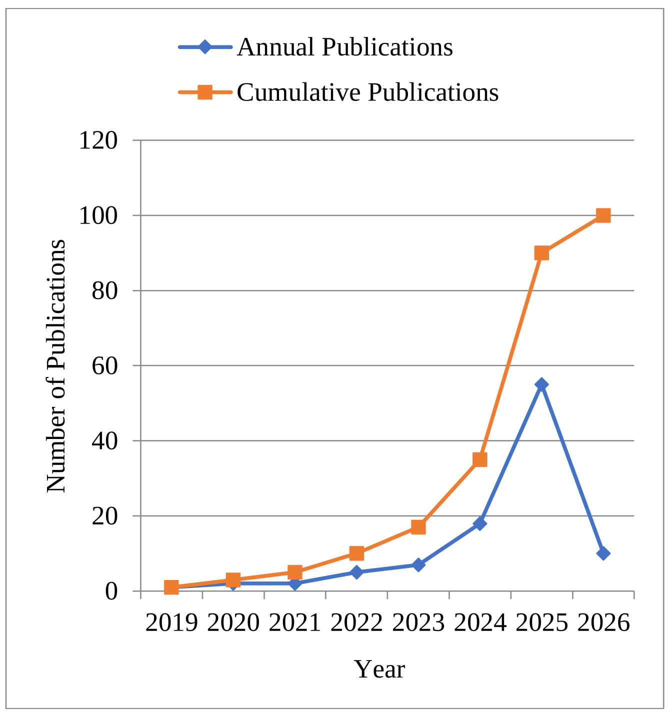

Fig. 3 Publication trend of PWMA research 2019-2026

PET and HDPE are the most prevalent research studies as Figure 4 demonstrates since they are available and also have good mechanical properties. Nonetheless, the lack of alternatives to polymers has also been investigated, which indicates a possibility to increase the range of materials. The result is in line with earlier research where it is emphasized that PET and HDPE are good modifiers to increase stiffness and rutting resistance [48-50]. However, the relatively low level of research on other polymers e.g. LDPE and composite plastics is a pointer that there is a potential research gap with respect to material diversity and methods of hybrid modification.

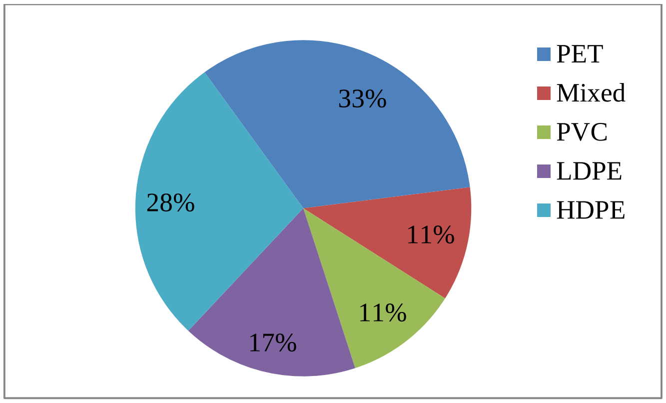

Fig. 4 Distribution of plastic types in PWMA studies

Figure 5 shows the distribution of computational approaches across the 36 reviewed studies. Machine learning was used in 20 studies (55.6%), deep learning in 12 studies (33.3%), and Explainable Artificial Intelligence (XAI) in 4 studies (11.1%). These results indicate that ML and DL approaches dominate the reviewed computational literature, whereas XAI remains comparatively less explored. Figuratively speaking, Figure 5 shows that the Machine Learning and Deep Learning approaches have a clear prevalence with a strong shift of the classical regression models towards an ensemble learning model and neural network-related architectures. This change aligns with the overall trends in the pavement engineering community, where data-driven models are becoming more commonplace because of their ability to model nonlinear material behavior [51, 52].

The analysis of the reviewed studies indicates that the research focus is predominantly concentrated on mechanical performance, particularly rutting resistance, stiffness, and Marshall stability. In contrast, environmental considerations are less frequently addressed and are generally limited to qualitative assessments or life-cycle analyses rather than predictive modeling [53].

In addition, the adoption of machine learning and deep learning techniques has increased in recent years; however, Explainable Artificial Intelligence (XAI) remains comparatively underexplored, with only 4 of the 36 reviewed studies (11.1%) incorporating XAI techniques. Among them, SHAP-based methods are only seen in isolated instances, which means that interpretability is hardly researched [10]. More critically, none of the studies that have undergone review provide a quantitative predictive model of microplastic release, which is a key shortcoming of the area, since it is paramount to balance mechanical optimization with the environmental impact assessment [54].

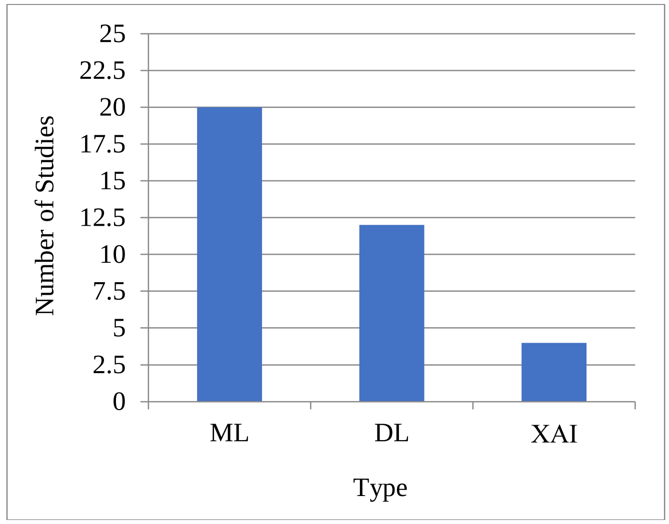

Fig. 5 Distribution of ML/DL/XAI algorithms

4.2. Comparative Performance of ML and DL Models

As the comparative analysis of predictive models, summarized in Table 4 (Comparative Performance of ML/DL Models) and visualized in Figure 6 (Model Performance Comparison Across Algorithms) indicate, Deep Learning (DL) models are more likely to have a higher level of predictive accuracy than the traditional Machine Learning (ML) predictive models. In particular, models including Multi-Layer Perceptron (MLP) and Neural Architecture Search-based ANN (NAS-ANN) can always attain a R^2 value of 0.95 and are therefore more successful than ensemble methods, like Random Forest (RF) and XGBoost in modeling complex rheological behavior.

Among the reviewed computational approaches, ANN and MLP generally reported high predictive performance, with reported R^2 values of 0.95. Their main advantage is the ability to represent complex nonlinear interactions among mixture and processing variables. However, their relatively low interpretability makes it difficult to explain how individual variables contribute to the predicted response. Random Forest (RF) reported R^2 values of 0.93 and provides greater robustness for structured datasets, although its predictive performance was generally lower than that reported for ANN/MLP in the reviewed studies. XGBoost achieved of 0.93 and represents a comparatively balanced option because it can provide strong predictive performance while requiring less computational complexity than some deep-learning and hybrid architectures. GEP produced of 0.94 and offers an additional advantage through mathematical expressions that can provide a more explicit representation of the relationship between variables, although its transparency and generalizability depend on the formulation and validation procedure used. Hybrid AI approaches produced the highest reported of 0.98, but this performance was associated with greater computational complexity and limited interpretability. These values are summarized in Table 4.

Table 4. Comparative performance of ML/DL models

Model Type	Representative Studies (RIS-based)	R^2	Strength	Limitation
ANN / MLP	Kumar and Kumar (2024) [34]	0.95	Excellent nonlinear modeling capability	Black-box, low interpretability
Random Forest	Kumar et al. (2024) [35]	0.93	Robust and stable	Lower accuracy compared to DL
XGBoost	Sadoudi et al. (2025) [10]	0.93	High predictive performance, efficient	Limited interpretability
GEP	Haider et al. (2024) [45]	0.94	Flexible modeling for rutting prediction	Low transparency
Hybrid AI	Sadoudi et al. (2025) [10]	0.98	Highest accuracy and adaptability	High computational complexity

Table 4 demonstrates that deep learning models, particularly ANN and MLP have a good predictive behavior with a high R^2 of 0.95. This confirms that they can depict the nonlinear relationships in PWMA systems that are complex. However, it is accompanied by a significant limitation in the interpretability, as most of the DL models are black-box systems.

On the other hand, ensemble-based methods (Random Forest and XGBoost) provide more balanced trade-offs between transparency and accuracy, thus are more useful in real-world engineering. The implication of these results is that accuracy cannot be applied to define the model selection but interpretability and computational efficiency should be considered.

As Figure 6 indicates, deep learning schemes, namely, MLP and NAS-based ones, are always best compared to traditional ML schemes with the greatest R^2 of 0.95. This high performance is attributed by the fact that they have the ability to capture nonlinear interactions among complexly natured inputs.

Nonetheless, this improvement in performance comes at the cost of interpretability and computational cost. Competitive accuracy with better robustness is offered by ensemble models like XGBoost which offer a more balanced result.

Nonetheless, there are trade-offs associated with this performance advantage. In spite of being more precise, DL models are more complicated and less interpretable. On the other hand, ensemble models such as XGBoost are more competitive and have stronger robustness and lower computational cost and can thus be more applicable to the realistic engineering application [55, 56].

The forecasting ability of Hybrid AI models (R^2 as high as 0.98), as shown in Table 4, is even more impressive since it integrates different approaches of optimization and learning. This increased accuracy, however, may often be obtained at the cost of increased complexity of the computations.

This fact substantiates the growing trend in the literature that no one best model exists but that the models used should be context-dependent and balanced in their accuracy, interpretability and computational efficiency [57, 58]. It is important to mention that R^2 value reported by various studies should be regarded with some skepticism because some studies utilize small datasets, or they are not externally validated as reported in Table 5. This brings about issues about the generalizability of the models and overfitting.

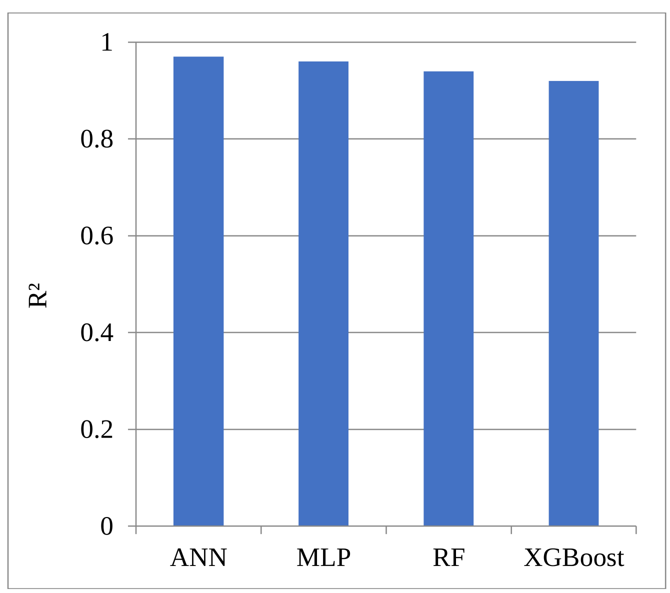

Fig. 6 Model performance comparison across algorithms

Table 5. Quality assessment and risk of bias evaluation

Study	Dataset Size	Validation Method	Metrics Reported	Overfitting Risk	Transparency
Sadoudi et al. (2025) [10]	Large	Cross-validation	R^2, RMSE	Low	High
Kumar and Kumar (2024) [34]	Medium	Train-test split	R^2, MAE	Medium	Medium
Gardezi et al. (2024) [37]	Small	Cross-validation	R^2, RMSE	Medium	Medium
Haider et al. (2024) [45]	Large	Cross-validation	R^2, RMSE	Low	High

4.3. Thematic Synthesis of the 36 Reviewed Studies

To provide a comprehensive synthesis, the 36 included studies were organized into five thematic clusters, as summarized in Table 6: ML/DL and predictive modeling, mechanical performance and mixture optimization, plastic-modified binder properties, sustainability and environmental applications, and review-based synthesis. This clustering approach provides a more representative overview of the complete review corpus and avoids overemphasizing repeatedly cited studies.

The literature is predominantly focused on mechanical performance, mixture optimization, and binder properties, while environmental assessment and explainability remain less developed.

In particular, predictive modeling of microplastic release is still limited, highlighting the need for integrated frameworks that combine mechanical performance, environmental outcomes, and interpretable computational modeling.

Table 6. Thematic synthesis of the 36 studies included in the review

Thematic Cluster	Number of Studies	Reference Numbers	Main Focus
ML/DL and predictive modeling	7	[8, 10, 34, 35, 37, 45, 60]	AI-based prediction and optimization
Mechanical performance and mix optimization	12	[5, 22, 23, 24, 29, 36, 43, 50, 53, 57, 59, 62]	Strength, rutting, moisture, dosage, and mix performance
Plastic-modified binder properties	6	[4, 16, 41, 49, 54, 65]	Rheology, stability, viscosity, and binder behavior
Sustainability and environmental applications	9	[9, 11, 21, 30, 32, 47, 52, 55, 56]	Recycling, environmental impact, LCA, and field application
Review and broader literature synthesis	2	[31, 33]	State of the art and research challenges

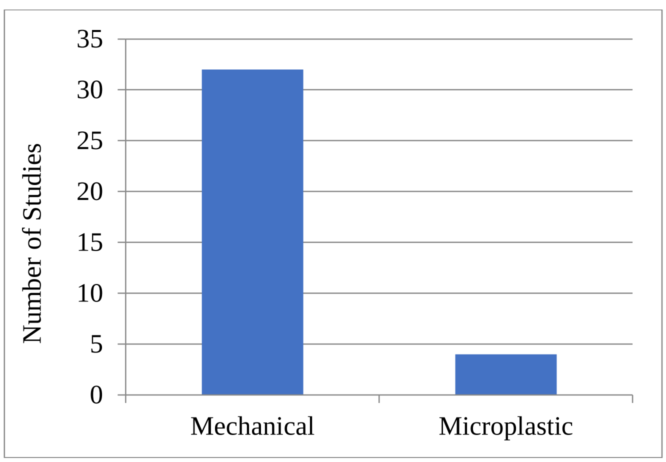

Fig. 7 Research gap: Mechanical vs microplastic studies

4.4. Microplastic Research Landscape and Environmental Gap

One of the most important conclusions of this review is the substantial imbalance between mechanical and environmental research in PWMA. Of the 36 studies reviewed, 32 studies (88.9%) primarily focused on mechanical performance, whereas only 4 studies (11.1%) addressed microplastic-related environmental issues, as shown in Figure 7 (Research Gap: Mechanical vs Microplastic Studies). The literature addressing microplastics is mainly based on experimental approaches, including laboratory abrasion tests or environmental sampling, and does not involve validated quantitative predictive modeling methodologies [59-61]. This contrasts with the extensive application of ML/DL models for predicting mechanical properties and highlights a major asymmetry in the development of PWMA research, particularly between mechanical-performance prediction and environmental-impact prediction.

Additionally, as Table 7 (Mapping of Mechanical, Environmental, and XAI Coverage) shows, there are few studies that even desire to integrate the mechanical and the environmental element into a single model. This discontinuity limits the analysis of the trade-offs between structural performance and environmental impact which is needed to develop sustainable pavement.

Table 7. Mapping of mechanical, environmental, and XAI coverage

Study Type	Mechanical	Microplastic	XAI
Mechanical-only studies	✓	✕	✕
Environmental studies	✕	✓	✕
ML/DL predictive studies	✓	✕	✕
Integrated studies	✓	✓	✓

Plastic Waste-Modified Asphalt (PWMA) and its environmental effects, especially the formation of microplastics were under-investigated in the existing literature. The formation of microplastics in asphalt pavements mainly occurs due to mechanical abrasion by the load of traffic, environmental weathering, and thermal degradation processes. The particles of the polymer-modified binder may be washed off by repeated vehicle loading, causing wear on the surface, and be carried to the ecosystems around them.

The variations in the temperature accelerate this process even more, with the alteration of the viscoelastic properties of the asphalt binder, which becomes susceptible to cracking and particle emissions. Additionally, oxidative aging is a contributory cause of brittle materials, thereby enhancing the breakdown of plastic-modified materials. Even though these already well-known mechanisms are in place, the existing literature is highly dependent on laboratory observations or environmental sampling, but not on predictive modeling methods [61-63]. The environmental studies are also preoccupied with detection and characterization as compared to prediction as shown in Table 8. This signifies that a gap in research is critical since a relationship between mechanical degradation and microplastic release has not been quantified.

Absence of integrated models that take into consideration both structural performance and environmental outcome limit the application of PWMA in sustainable infrastructure development [64-66]. Thus, to develop a balanced and responsible engineering solution, the use of microplastic prediction in the framework of data is critical, as suggested in this study.

Table 8 summarizes the current state of research in Plastic Waste-Modified Asphalt (PWMA) with the various types of materials, the way in which the computational models are conducted, and the environmental issues. The discussion reveals that most of the studies can attain high predictive accuracy of mechanical properties, such as, Marshall stability, rutting resistance, penetration and moisture damage. Nevertheless, most of these studies are still grossly concerned with structural performance, whereas environmental effects, especially the release of microplastics are given minimal coverage. Even those studies that involve sustainability debates are usually based on Life Cycle Assessment (LCA) or qualitative reviews as opposed to quantitative predictive analysis.

Notably, explainable AI methods are hardly used, as the table indicates. Most machine learning and deep learning systems are black-box systems, which limits their use in decision-making in engineering. Mathematical formulations or analysis of limited features partially cover the interpretability in few studies. This last row places the study as a new contribution by suggesting an Explainable Deep Learning (XDL) framework that can concurrently predict the mechanical performance and release of microplastic and is completely interpretable with SHAP, LIME, and PDP. This directly completes the research gap which is vital in the process of the literature review.

Table 8. Key variables influencing PWMA performance

Variable	Influence on Mechanical	Influence on Microplastic	Importance Level
Plastic dosage	High	High	Critical
Mixing temperature	High	Medium	High
Binder composition	Medium	Medium	Moderate
Traffic load	High	High	Critical
Aging condition	Medium	High	High

4.5. Research Gaps and Future Research Directions

The reviewed literature reveals several important research gaps. Existing studies mainly focus on the mechanical performance of PWMA, while microplastic release and environmental consequences remain less investigated. Although ML and DL models show promising predictive performance, limited external validation, small and heterogeneous datasets, and insufficient field data restrict their generalizability to real pavement conditions. Most studies also focus on single-output prediction, with limited integration of mechanical and environmental outcomes. Furthermore, uncertainty quantification and XAI remain insufficiently integrated, while the connection between predictive modeling, LCA, and multi-objective optimization is still limited. Future research should therefore emphasize standardized microplastic testing, field-informed datasets, external validation, multi-output ML/DL, uncertainty analysis, LCA, and multi-objective optimization. Integrating these approaches with XAI could provide more transparent and reliable decision support for sustainable PWMA design and lifecycle management.

Table 9. Synthesis of Machine Learning and Deep Learning applications in PWMA

Study Cluster (References)	Modifier Type & Dosage	Primary AI/DL Algorithm	Explanatory Technique (XAI)	Target Mechanical Output	Target Environmental Output	Peak Performance / Key Synthesis Finding
Kumar and Kumar (2024) [34]; Kumar et al. (2024) [35]	Waste Plastic (5–15%)	ANN, SVM, Tree-based Models	None (Black-box)	Marshall Stability, Flow Value	None	High predictive accuracy ($R^2 > 0.95$); effective in identifying optimum plastic dosage but lacking interpretability
Gardezi et al. (2024) [37]; Haider et al. (2024) [45]	Mixed Plastic + RAP + Fly Ash	GEP	Partial (Mathematical formulation only)	Rutting Depth, Moisture Damage	None	Strong prediction of performance degradation and rutting resistance; improved understanding of nonlinear material behavior
Sadoudi et al. (2025) [10]	Modified Bitumen with Plastic Additives	Hybrid AI Models	Limited Feature Analysis	Penetration, Softening Point	None	Exceptional predictive performance (R^2 up to 0.98), but computationally expensive and low interpretability
Mohammadi and Ameri (2024) [38]; Bilema (2024) [33]	Various Plastic Waste Types	Review + Sustainability Assessment	Not Applicable	Mechanical Performance Review	Environmental Impact Assessment	Identified significant research imbalance: strong focus on mechanics, weak focus on microplastic prediction
Salehi (2024) [30]; Lim et al. (2024) [32]	Recycled Plastic Pavement	Life Cycle Assessment (LCA)	None	Recyclability Potential	Environmental Impact, Microplastic Risk	Environmental impacts acknowledged, but no predictive AI model for microplastic release

5. Conclusion

This study provides a systematic literature review of the use of the state-of-the-art computational modeling of plastic waste-modified asphalt, particularly on the integration of the forecasting of mechanical performance and the sustainability of the environment. Based on the summary of 36 peer-reviewed studies, it is possible to point out some significant results.

First, it has been consistently observed that recycled thermoplastics, specifically, Polyethylene Terephthalate (PET), High-Density Polyethylene (HDPE) and Polyvinyl Chloride (PVC) enhance the mechanical properties of asphalt mixtures, especially, in terms of stiffness and resistance to rutting. The prediction of such behaviors by ML and DL algorithms has proven to be very predictive and many studies have established high-performance indicators ($R^2 > 0.95$). Among them, Multi-Layer Perceptron (MLP) and Neural Architecture Search-based models are Deep Learning architectures that are more precise than traditional ML methods but are more complex and less understandable.

Second, there is a major disproportion between mechanical and environmental studies in PWMA. Though the majority of the research has been performed with regard to the structural performance, very little research has been undertaken on the issue of microplastic release. The existing literature on microplastics is primarily experimental and lacks predictive modeling models hence posing a significant gap of lack of ability to estimate the impacts of the environment in realistic pavement conditions.

Third, the review concludes that there is a considerable gap in the current modeling practices that is explained. Even though the ML/DL models are precise, they are inapplicable in the field of engineering the decisions because they are black-box models. The use of Explainable Artificial Intelligence (XAI) is still under-explained, and a very small fraction of the literature employs either SHAP or LIME to interpret model predictions. This weakness of interpretability is an obstacle to the understanding of the complex interrelationships between material characteristics, processing conditions and performance outcomes.

Fourth, this paper brings into the limelight a much needed but less studied trade-off between mechanical performance and environmental sustainability. Even though plastic content improves the structural properties, it may cause the materials to be brittle as well as degrade the surface of the materials, which may ultimately increase the release of microplastics. Lack of integrated models that will be able to examine these competing effects in a single study is one of the greatest limitations of the existing research. To address these shortcomings, this research paper will introduce a novel Explainable Deep Learning (XDL) architecture that can be seen as a hybrid between the predictive power of Deep Learning and the explainability of XAI techniques. The suggested framework allows predicting both the mechanical performance and microplastic release simultaneously and understanding the role of the important input variables. The strategy is an important move towards closing the discontinuity between high-precision modeling and engineering feasibility.

This study has a number of limitations in spite of its contributions. The search will also be restricted to peer-reviewed journal articles of the last 3 years (2019-2026) and exclude non-English articles and conference papers, which may cause selection bias. Also, the differences in the nature of data set and models used in studies discourage the comparability of results.

Future research should focus on the development of multi-objective optimization models with structural performance and environmental impact. There should also be standardized experimental protocols to provide a measurement of microplastic release that would lead to the generation of stronger and more generalizable predictive models.

In addition, combination of PWMA modeling and hydrological and runoff simulations would be useful in offering a more in-depth insight into the transport of microplastic in the real world. Finally, real-time, information-driven decision-support systems based on XDL frameworks have tremendous potential in creating sustainable pavement engineering.

In conclusion, the paper under consideration creates a decisive basis in regard to incorporating high-order computational modeling and environmental sustainability in the research of PWMA. It can be used to create more transparent, accurate, and environmentally-friendly pavement design processes as it identifies the key gaps in the existing XDL and proposes a new XDL framework.

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