

Sustainable Asphalt Mixtures Using Agricultural Waste Fillers: A Systematic Review of Rice Husk Ash, Bagasse Ash and Palm Shell Ash

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Abstract

The increasing demand for environmentally sustainable road infrastructure has led to a growing interest in replacing conventional mineral fillers in asphalt mixtures with agricultural waste-based alternatives. This systematic review examines the potential of rice husk ash (RHA), Bagasse Ash (BA), and Palm Shell Ash (PSA) as fillers in Asphalt Concrete – Binder Course (AC-BC) mixtures. A total of 72 peer reviewed studies published between 2010 and 2024 were analysed, focusing on key Marshall parameters: stability, flow, Void in Mix (VIM), Voids Filled with Bitumen (VFB), Voids in Mineral Aggregate (VMA) and Marshall Quotient (MQ). The review highlights that RHA and BA significantly improve stability and stiffness, with optimal performance typically at 6-8% and 4-6% filler content by weight, respectively. PSA, on the other hand, enhances flow and workability, performing best at 5-7% dosage. All three ashes demonstrate the potential to reduce VIM and VMA while increasing VFB, contributing to denser and more moisture resistant mixtures. However, the performance strongly depends on filler characteristics such as particle fineness, silica content, and carbon residue. Although these agro-waste fillers offer promising benefits in terms of sustainability and mechanical performance, challenges remain regarding standardization, processing, and field application. Further research is required to validate long-term durability and support large-scale implementation.

Keywords

Asphalt Concrete - Binder Course; Marshall test; Rice Husk Ash; Bagasse Ash; Palm Shell Ash.

1. Introduction

The transition toward sustainable infrastructure is a global priority, especially in Indonesia, where flexible pavement is dominant due to its cost-efficiency and adaptability. The mineral filler in asphalt concrete critically influences pavement performance, traditionally using Portland Cement or stone dust (Remisova, 2015), (Chindaprasirt et al., 2021). However, rising environmental concerns and increasing industrial and agricultural waste have driven the exploration of biomass-derived fillers as sustainable alternatives (Putri et al., 2022), (Putri et al., 2020), (Fayissa et al., 2020).

In recent years, the use of agricultural waste materials as an alternative filler has gained growing attention due to their environmental benefits and local availability, especially in regions with high agricultural output (Fayissa et al., 2020b). Materials such as Rice Husk Ash (RHA), Bagasse Ash (BA) and Palm Shell Ash (PSA) not only offer potential cost savings but also contribute to circular economy practices by reducing landfill waste. Several studies (Mashaan et al., 2014), (Baffoe & Ghahremaninezhad, 2022) have highlighted their influence on mechanical performance and sustainability indicators in asphalt mixtures. However, a consolidated comparison of these materials under a unified review framework is still lacking.

Agricultural by-products like rice husk ash (RHA), bagasse ash (BA), and palm shell ash (PSA) exhibit high pozzolanic activity and are regionally abundant (Mistry et al., 2019). These materials can enhance asphalt mixture performance while reducing waste (Arabani & Tahami, 2017a). Previous studies report improvements in mechanical properties such as stability and stiffness with these ashes, though comparative analyses remain limited (Mistry et al., 2019).

This review synthesizes research on RHA, BA, and PSA as fillers in AC-BC mixtures, assessing their impact on Marshall properties, discussing advantages, limitations, and feasibility for sustainable road construction, and outlining future research directions.

2. Methodology

This study employed a systematic review approach to evaluate the effects of agricultural waste-based fillers RHA, BA and PSA on the performance of Asphalt Concrete – Binder Course (AC-BC) mixtures. The review followed five main stages: literature review identification, screening, eligibility assessment, data extraction, and categorisation.

2.1. Literature Identification

A comprehensive search was conducted in four academic databases: Scopus, ScienceDirect, Google Scholar, and Garuda, covering the publication period 2010 to 2024. The key used included: “asphalt concrete”, “agricultural waste filler”, “rice husk ash”, “bagasse ash”, “palm shell ash”, “Marshall stability” and ‘Marshall parameters’ (Ali & Al-Tameemi, 2025).

2.2. Screening and Eligibility Criteria

Studies were initially screened based on their titles and abstracts to exclude unrelated articles. Eligible studies were required to:

- a. Use RHA, BA, or PSA as partial or full filler replacements.
- b. Evaluate at least one Marshall parameter (stability, flow, VIM (Void In Mix), VMA (Void in Mineral Aggregate), VFB (Void Filled with Bitumen), and MQ (Marshall Quotient) (Kareem et al., 2024a).
- c. Report clear filler dosages and experimental procedures.

2.3. Data Extraction

Selected studies were reviewed in full text. Relevant data were extracted into a structured table, including:

- a. Type and source of filler.
- b. Filler dosage (in % by weight).
- c. Reported Marshall test results.

- d. Observed threads and limitations.

2.4. Study Categorization

Extracted studies were grouped by filler type (RHA, BA, PSA) and analysed for performance consistency across dosages. This enabled comparison of trends and identification of optimum content ranges. Where available, data and non-experimental works were excluded.

2.5. Quality Control

To ensure review reliability, only peer-reviewed journal articles and conference papers were considered. Duplicate data and non-experimental works were excluded. Methodology ensured transparency, rigour, and actionable insights for infrastructure applications as seen in Table 1.

Table 1: Systematic review methodology stages.

Methodological stage	Activity description	Main output/Result	Reference
Literature identification	Article searches were conducted in Scopus, ScienceDirect, Google Scholar, and Garuda using keywords related to ash-based fillers and asphalt (2010–2024).	Initial collection of relevant studies.	(Putri et al., 2022)
Initial screening	Selection based on title and abstract to eliminate irrelevant studies.	List of potentially relevant studies for further review.	(Arabani & Tahami, 2017a)
Eligibility assessment	Full-text review ensured studies used RHA, BA, or PSA as fillers and reported Marshall parameters per inclusion criteria.	Studies eligible for analysis.	(Mistry et al., 2019)
Data extraction	Collecting primary data from each study (type and source of filler, dosage, Marshall parameters, performance trends).	Structured dataset from selected studies.	(Remisova, 2015), (Putri et al., 2020)
Study categorization	Grouping studies based on filler type (RHA, BA, PSA) for focused analysis.	Study categories by type of ash.	(Mistry et al., 2019), (Arabani & Tahami, 2017)

3. Results and Discussions

3.1. Marshall Stability and Flow

RHA enhances Marshall stability at 6–8% filler content due to its high silica and angular shape, improving binder interaction and stiffness (Arabani & Tahami, 2017b), (Ragab & Abo El-Naga, 2022). Its pozzolanic activity boosts cohesion and deformation resistance (M. N. N. Khan et al., 2015), (Lu et al., 2020). However, excessive RHA increases brittleness, so optimal dosage is crucial to balance strength and flexibility in asphalt mixes (Fareed et al., 2020), (Rahmouni et al., 2019), (Nava Bravo et al., 2019).

BA enhances asphalt stability through angular texture and silica content (Zainudin et al., 2016),(Sarir et al., 2025), (Jwaida et al., 2024), (F. de A. Silva et al., 2011), (Liu et al., 2020). Performance depends on particle fineness and carbon content; fine, low-carbon BA improves packing and binder adhesion, while coarse or carbon-rich ash reduces homogeneity (Rahmouni et al., 2019), (Nava Bravo et al., 2019), (Zhang et al., 2020). Proper processing ensures consistent improvements in mixture stability and flow (Fjelsted et al., 2020).

PSA offers moderate stability but markedly enhances flow characteristics due to its fine particles and mineralogy (Pelisser et al., 2010), (T.-A. De Silva & Forbes, 2016), (Shi & Reitz, 2010), (Chaudhuri et al., 2018). This promotes flexibility under traffic and thermal stresses (Jwaida et al., 2024), (Amanda et al., 2025). Although PSA may not ensure peak stability,

its ductility benefits mitigate cracking risks (Chan et al., 2019). Moreover, PSA supports palm oil waste valorisation, reinforcing sustainability goals in asphalt pavement design (Patel et al., 2017), (Naqvi et al., 2019). A comparative summary of these effects on stability and flow characteristics is presented in Table 2.

Table 2: Effects of RHA, BA and PSA on stability and flow characteristics.

Filler type	Effect on Marshall stability	Effect on flow	Key technical notes	Reference
Rice Husk Ash (RHA)	Increases stability at optimal content (6–8% by weight); excessive use may induce brittleness and reduce ductility.	Generally, it maintains acceptable flow; excessive content may decrease ductility.	High silica content and angular morphology improve binder-filler interaction; dosage optimization is crucial.	(Arabani & Tahami, 2017b), (Ragab & Abo El-Naga, 2022), (M. N. N. Khan et al., 2015), (Lu et al., 2020), (Fareed et al., 2020), (Rahmouni et al., 2019), (Nava Bravo et al., 2019)
Bagasse Ash (BA)	Increases stability via angular particles; varies with fineness and carbon content.	Maintains or slightly improves flow; excessive carbon or coarse particles may reduce homogeneity.	Fineness and residual carbon content are critical for performance; proper processing is needed.	(Zainudin et al., 2016), (Sarir et al., 2025), (Jwaida et al., 2024), (F. de A. Silva et al., 2011), (Liu et al., 2020), (Rahmouni et al., 2019), (Nava Bravo et al., 2019), (Zhang et al., 2020)
Palm Shell Ash (PSA)	Yields moderate stability compared to RHA and BA.	Greatly improves flow, enhancing workability and deformation tolerance.	Fine particle size and mineral composition enhance flexibility; suitable for dynamic loading conditions.	(Pelisser et al., 2010), (T.-A. De Silva & Forbes, 2016), (Shi & Reitz, 2010), (Chaudhuri et al., 2018), (Amanda et al., 2025) [23],[24],[25], (Chan et al., 2019), (Patel et al., 2017), (Naqvi et al., 2019)

Table 2 shows RHA and BA significantly enhance Marshall stability and stiffness when optimally dosed, while PSA improves flow and flexibility, vital for variable loading. Filler selection must balance mechanical performance, local agricultural waste availability, and pavement-specific requirements for sustainable application.

3.2. Voids Content (VIM, VMA)

Agro-waste fillers like rice husk ash (RHA), bagasse ash (BA), and palm shell ash (PSA) typically reduce Voids in Mix (VIM) and Voids in Mineral Aggregate (VMA), indicating better particle packing and densification. Finer, angular ashes fill inter-aggregate voids more efficiently, improving mix compactness and durability (Fareed et al., 2020), (Zhang et al., 2020).

RHA's fine particles and high silica content effectively reduce VIM and VMA at 6–8% filler content (Mohajerani et al., 2017), (Shafabakhsh et al., 2018). Angular and porous, RHA promotes interlock with aggregates, enhancing load transfer and reducing air voids (Raj et al., 2023). However, excessive RHA may cause over-compaction, lowering voids below optimal limits and impairing moisture resistance (Mistry & Kumar Roy, 2021).

BA also reduces voids, provided it's finely ground and low in residual carbon (Yoo et al., 2016), (Kim et al., 2024). Properly processed BA enhances density and reduces permeability (Buritatum et al., 2022). Coarse or carbon-rich BA may limit void reduction and weaken cohesion (Yoo et al., 2016).

PSA provides the greatest reduction in VIM and VMA due to its fine size and mineralogy (Ramdhani et al., 2025), (Oktavia et al., 2022). This densifies mixtures and boosts rutting resistance. Yet, excessive PSA can lower air voids too much, risking bleeding and limiting thermal flexibility (Doğruyol & Durmaz, 2025).

The influence of RHA, BA and PSA on VIM and VMA can be observed in Table 3, which summarises the reported trends across different filler contents.

3.3. Voids Filled with Bitumen (VFB)

The use of RHA, BA, and PSA reduces VIM and VMA, increasing VFB and improving cohesion and impermeability (Tiwari et al., 2023), (Liang et al., 2023). Maintaining optimal VFB prevents bleeding and ensures skid resistance (Hermansyah et al., 2022). Proper control of filler content and characteristics enhances density, durability, and moisture resistance in asphalt mixtures. As shown in Table 3, the VFB values tend to increase with filler addition indicating improved compact ability of the mixtures.

Table 3: Effects of RHA, BA and PSA on void characteristics.

Filler type	Effect on VIM	Effect on VMA	Effect on VFB	Key considerations	Reference
Rice Husk Ash	Reduces (optimal)	Reduces (optimal)	Increases	Risk of over-compaction at high content	(Mohajerani et al., 2017), (Shafabakhsh et al., 2018), (Raj et al., 2023), (Mistry & Kumar Roy, 2021)
Bagasse Ash	Reduces (if fine)	Reduces (if fine)	Increases	Effectiveness depends on fineness and carbon content	(Yoo et al., 2016),(Kim et al., 2024), (Buritatum et al., 2022)
Palm Shell Ash	Most reduction	Most reduction	Most increase	Superior densification; risk of bleeding if excessive	(Ramdhani et al., 2025), (Oktavia et al., 2022), (Doğruyol & Durmaz, 2025)

Table 3 highlights the importance of filler type, fineness, and dosage in modifying the void structure of asphalt mixes. Each ash type brings distinct benefits and considerations, making its selection critical to achieving optimal asphalt performance.

3.4. Marshall Quotient (MQ)

The Marshall Quotient (MQ), defined as the ratio of Marshall Stability to Flow, is a critical indicator of an asphalt mixture’s stiffness and its resistance to permanent deformation under load.(Taherkhani, 2016) A higher MQ value reflects a stiffer, more rut-resistant mix, while a lower MQ indicates greater flexibility but potentially less resistance to deformation (Taherkhani, 2016).

RHA enhances MQ up to an optimal 6–8% dosage, driven by its high silica and angular, porous particles that improve aggregate-binder interlocking (Damanhuri et al., 2020). This increases stiffness and rutting resistance for traffic-bearing pavements. Excess RHA (>8%) can cause brittleness and cracking (Du et al., 2018). Optimal dosing is key for balancing flexibility and stiffness (Guo et al., 2025).

Finely ground BA at 5–10% improves MQ through angularity and surface roughness that boost interlocking and binder adhesion (Sarir et al., 2025), (Sarir et al., 2022), (Zia & Khan, 2021). Fineness and low residual carbon are crucial, as unburnt matter can reduce stiffness.

PSA's fine particles and minerals improve packing, stability, and rutting resistance via enhanced binder interaction, significantly raising MQ and durability (Omoremiju et al., 2024). In experimentation using palm shell ash fillers at varying content, the addition of PSA notably improved Marshall parameters while offering cost-effective regional agro-waste (Tambunan, 2025). PSA-modified mixes maintain workability, aiding field application, with optimal content at 5–10%. Excess PSA, like RHA and BA, may reduce fatigue life (N. Khan, 2021).

Therefore, within the range of 5-7% PSA content by weight, PSA demonstrates the highest MQ among the three fillers, suggesting it as the most suitable option in terms of mechanical performance, local availability, and economic sustainability. A comprehensive comparison of these effects on Marshall quotient, including optimal dosage ranges and technical implications, is summarised in Table 4.

Table 4: Effects of RHA, BA and PSA on Marshall quotient.

Filler type	Typical optimal content (% by weight of filler)	Effect on Marshall quotient (MQ)	Technical explanation / Key findings	Practical implications	Reference
Rice Husk Ash (RHA)	6–8%	Increases MQ up to optimal content; excessive use may reduce flexibility	High silica and angular, porous particles enhance interlocking and stiffness; excessive RHA can cause brittleness and cracking.	Good for rutting resistance; needs dosage optimization	(Damanhuri et al., 2020), (Du et al., 2018), (Guo et al., 2025)
Bagasse Ash (BA)	5–10%	Moderate increase in MQ at optimal dosage	Angularity and rough surface improve binder adhesion and stability; unprocessed BA (with residual carbon) may lower MQ.	Enhances deformation resistance; quality control needed	(Sarir et al., 2022), (Zia & Khan, 2021), (Nava Bravo et al., 2019)
Palm Shell Ash (PSA)	5–10%	Highest MQ among the three fillers	Fine particle size and mineral composition improve particle packing, stability, and stiffness; maintains good workability.	Best for high stiffness and rutting resistance	(Omoremiju et al., 2024)

The use of agricultural waste ashes as filler in asphalt mixture has shown a notable effect on Marshall Quotient. As presented in Table 4 shows RHA and BA boost stability via silica and angularity, while PSA enhances flow. Filler performance depends on particle traits and dosage optimization. Based on comparative MQ values and supported by (Fitra Ramdhani et al., 2024) PSA shows the highest MQ among the reviewed fillers, making it the most effective and sustainable option.

3.5. Environmental and Practical Implications

RHA abundant in rice regions is a waste with slow decomposition (During et al., 2018) (Pachchigar et al., 2024). Its asphalt use reduces pollution and landfilling, while silica content improves stiffness and rutting resistance (Raj et al., 2023) . However, consistent ash quality requires controlled burning. Standardised production and uniform particle size are crucial for performance reliability (Kartini et al., 2012), (Wagan et al., 2022).

BA, a sugarcane byproduct, is abundant in tropical sugar mills (Kartini et al., 2012), (Raza et al., 2021). Its use in asphalt supports circular economy goals (Raza et al., 2021), (Adeoti et al., 2025). With pozzolanic properties, finely processed BA enhances stability and moisture resistance (Bayapureddy et al., 2024). However, chemical variability and unburnt carbon can impair adhesion and uniformity (Aprianti et al., 2015). Pre-treatment is often needed, increasing implementation complexity and cost (Yadav et al., 2020).

PSA originates from palm oil waste (Ikumapayi & Akinlabi, 2018). Using it as filler mitigates waste issues and carbon emissions. PSA’s fine particles improve mix workability and stiffness for heavy-traffic roads (Inyang et al., 2024). Due to lower reactivity than RHA or BA, optimal PSA use requires blending or dosage control. Consistent quality is vital for broader use (Torres-Ortega et al., 2024). A summary of the environmental and practical implications of using RHA, BA, and PSA as asphalt fillers can be seen in Table 5.

3.6. Shared Benefits and Challenges

Using RHA, BA, and PSA as asphalt fillers reduces dependence on mineral fillers and diverts agro-waste from landfills, lowering pollution and supporting sustainability goals (Fareed et al., 2020), (Kareem et al., 2024b). These fillers cut material costs near agricultural sources and enhance mechanical properties, extending pavement life (Ali & Al-Tameemi, 2025). However, challenges include inconsistent ash quality, limited field validation, and uncertain long-term

performance. Addressing standardisation, moisture resistance, and large-scale logistics is essential for sustainable, durable infrastructure (Jain et al., 2024). A summary of the environmental and practical implications of using RHA, BA, and PSA as asphalt fillers, highlighting the benefits, challenges, and regional suitability based on current literature, can be seen in Table 5.

Table 5: Environmental and practical implications of RHA, BA and PSA as asphalt fillers.

Filler type	Environmental benefits	Practical implications	Key challenges & considerations	Reference
Rice Husk Ash (RHA)	- Reduces rice husk waste and open burning. - Lowers landfill burden. - Cuts carbon footprint.	- Enhances stiffness and rutting resistance. - Readily available in rice-producing regions.	- Requires controlled burning for quality. - Needs particle size standardization.	(Pachchigar et al., 2024), (Kartini et al., 2012), (Raj et al., 2023)
Bagasse Ash (BA)	- Utilizes sugarcane industry byproduct. - Supports circular economy. - Reduces waste disposal.	- Improves moisture resistance and stability (when fine). - Potential for low-cost filler in sugarcane regions.	- Quality varies with processing. - May need pretreatment to remove unburnt carbon.	(Raza et al., 2021), (Adeoti et al., 2025), (Bayapureddy et al., 2024), (Aprianti et al., 2015), (Jain et al., 2024)
Palm Shell Ash (PSA)	- Valorises palm oil industry waste. - Reduces environmental pollution. - Lowers carbon emissions.	- Increases workability and flexibility. - Suitable for heavy-traffic areas. - Locally abundant in palm oil regions.	- Lower pozzolanic reactivity than RHA/BA. - Needs consistent sourcing and processing.	(Ikumapayi & Akinlabi, 2018), (Inyang et al., 2024), (Torres-Ortega et al., 2024)

Table 5 demonstrates that RHA, BA, and PSA reduce landfill waste and asphalt carbon footprints. Regionally sourced RHA/BA benefit rice/sugarcane sectors; PSA suits palm industries. While promoting sustainable infrastructure, standardised processing and field validation require prioritisation for scalability and long-term performance.

3.7. Critical Discussion

The summary of this review research is presented in Table 6.

Table 6: Summary review of RHA, BA and PSA as asphalt fillers.

Filler type	Optimal content (%)	Effect on stability	Flow	MQ	Notes
RHA	6–8	↑↑	↔	↑↑	High SiO ₂ , best stiffness gain
BA	4–6	↑	↔	↑	Sensitive to carbon content
PSA	5–7	↑	↑↑	↔	Enhances flexibility

(↑ = increase, ↔ = neutral trend)

Table 6 evaluates RHA, BA, and PSA fillers by optimal content and performance. RHA (6–8%) yields the highest stability and stiffness. BA (4–6%) offers moderate gains, while PSA (5–7%) improves flexibility. Performance depends on composition, dosage, and processing. Excess filler impairs dispersion, increasing voids and reducing durability.

4. Conclusions

This study aimed to evaluate the use of agricultural waste ashes systematically Rice husk ash (RHA), Bagasse Ash (BA), and Palm Shell Ash (PSA) as sustainable fillers in Asphalt Concrete-Binder Course (AC_BC) mixtures. The review was conducted to identify optimal usage ranges and assess their influence on mechanical properties, particularly Marshall parameters. The findings reveal that:

- a. RHA enhances Marshall stability and stiffness, with optimal performance at 6-8% filler content by weight.
- b. BA shows moderate improvements in both stability and density, particularly when finely processed and used at 4-6% content.
- c. PSA contributes significantly to mixture flow and flexibility, yielding the best result a dosage of 5-7%.

All the fillers reduce Void in Mix (VIM) and Voids in Mineral Aggregate (VMA) while increasing Void Filled with Bitumen (VFB), thereby improving mix compactness and potential moisture resistance. PSA achieved the highest Marshall Quotient (MQ) values at 5-10% content, suggesting its suitability for high-load, flexible pavement.

Despite their potential benefits, the practical application of these agro-waste filler is challenged by variability in ash properties by variability in ash properties by variability in ash properties, the need for standardization, and a lack of field validation. Therefore, future research should prioritize.

- a. Developing uniform processing methods for ash-based fillers.
- b. Conducting long term field performance studies.
- c. Assessing economic feasibility and environmental trade offs in real world contexts.

These efforts will support and contribute to more sustainable and cost-effective pavement strategies, especially in regions with high agro-waste availability.

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Author Contributions

L.P. contributed to the conceptualisation of the article, the design of the review methodology, and the initial drafting of the manuscript. **E.E.P.** was responsible for a comprehensive literature review, thematic organisation of findings, and development of visual summaries. **B.M.A** contributed to the critical analysis and synthesis of the reviewed studies, identifying key trends and research gaps. **A. A** Reviewed and edited the manuscript for clarity and coherence, and managed reference formatting and citations.

Disclosure of Interest

The authors confirm that there are no conflicts of interest associated with this publication, whether financial or personal, that could have influenced its content.

Data Availability Statement

This article is a review of existing literature. The referenced datasets are available in the original published articles, as cited in the manuscript.

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