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Bio-bitumen Technique for Eco-Friendly Management of Agricultural Waste: Advances, Current Status and Future Perspectives

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Abstract:
Agricultural waste generation is increasing worldwide due to intensification of cropping systems, agro-processing expansion, and rising consumption. While residues such as rice husk, wheat straw, sugarcane bagasse, coconut shells/husks, palm oil biomass, and olive pomace are often valorized through combustion, composting, bioenergy, or bioproducts, large fractions still remain underutilized and may be openly burned or dumped, causing air pollution, greenhouse-gas (GHG) emissions, and soil and water impacts. In parallel, the road sector relies heavily on petroleum bitumen, and conventional asphalt mixtures consume large quantities of mineral filler and aggregates, contributing to resource depletion and embodied emissions. The "bitumen technique" for agricultural waste management—broadly defined as the incorporation of agricultural wastes (directly or after conversion to ash, biochar, lignin, bio-oil, fibers, or hybrid derivatives) into bituminous binders and asphalt mixtures—has emerged as an engineering pathway that couples residue management with infrastructure development. This review synthesizes advances in (i) agricultural waste ashes (e.g., rice husk ash, bagasse ash, palm oil fuel ash, wheat straw ash) as mineral fillers or binder modifiers; (ii) lignin-based and bio-bitumen approaches that partially substitute petroleum bitumen; (iii) biomass-derived bio-oils and bio-binders; (iv) biochar/nano-ash systems to improve rutting and aging resistance; and (v) composite strategies integrating waste plastics, rubber, and agricultural residues to optimize performance. The current status indicates that properly processed agricultural residues can enhance stiffness, rutting resistance, and in some cases durability—though low-temperature cracking, moisture susceptibility, heterogeneity, and long-term aging remain key concerns dependent on residue type, dosage, and processing route. Emerging life-cycle assessments suggest potential climate benefits for certain bio-bitumen pathways, but trade-offs (e.g., land use, sourcing, logistics) require careful governance. The review highlights practical protocols, characterization methods, mixture design considerations, performance trends, environmental and techno-economic implications, and research gaps. Finally, future perspectives are proposed for scalable deployment, including residue supply-chain certification, standardization, multi-objective mixture optimization, field trials in diverse climates, circular procurement, and integration with low-temperature asphalt technologies.

Keywords: agricultural residues; bitumen modification; asphalt; rice husk ash; sugarcane bagasse ash; lignin; bio-bitumen; bio-oil; biochar; circular economy; life-cycle assessment

1. Introduction

Agricultural systems and agro-industries generate vast quantities of lignocellulosic residues and by-products. In many regions, a significant share is managed informally via open burning or dumping, leading to particulate emissions, smog episodes, black carbon release, and loss of potentially valuable biomass resources. Meanwhile, road infrastructure demand continues to rise, particularly in rapidly developing economies, and asphalt pavements remain dominant due to cost-effectiveness and constructability. Asphalt production, however, depends on petroleum bitumen and quarried mineral aggregates/fillers, creating a large materials footprint.

The concept of using agricultural waste within bituminous materials connects two material flows: (1) residues that require environmentally sound management and (2) pavement materials that require large volumes of filler/binder and can tolerate engineered variability if performance targets are met. Over the last decade, research has expanded from conventional ash fillers to nano-scale ashes, biochar, lignin-based substitutes, and bio-oils that act as rejuvenators or partial binders.

A key driver behind this transition is the maturity of asphalt materials engineering: binder rheology can be tailored by modifiers; mixtures can be designed to balance rutting, fatigue, and moisture resistance; and performance tests (e.g., dynamic shear rheometer, BBR, wheel tracking) provide robust screening. Agricultural wastes—when processed into controlled powders, ashes, bio-oils, or lignin fractions—can interact with bitumen through physical filling, adsorption, polar interactions, chemical functional group contributions, and microstructural reinforcement.

This review uses “bitumen technique” as an umbrella term covering:

1. agricultural waste ashes as fillers or binder modifiers,
2. lignin/bio-bitumen partial substitution,
3. biomass bio-oils as modifiers/rejuvenators,
4. biochar/nano-ash systems, and
5. hybrid circular mixtures involving multiple waste streams.

2. Agricultural waste streams relevant to bitumen/asphalt systems

Residues differ widely in composition, ash chemistry, morphology, and processing requirements. Commonly studied agricultural wastes include:

- **Rice husk and rice straw:** high silica content in husk ash; straw ash variable depending on soil contamination and burning conditions. Rice husk ash (RHA) is widely evaluated as a modifier and filler (Han et al., 2017).
- **Sugarcane bagasse and bagasse ash (SBA/SCBA):** ash contains silica, alumina, and unburnt carbon depending on combustion; multiple studies report feasibility as filler replacement in hot mix asphalt (Šimun et al., 2023; Hipólito et al., 2024; Imoh et al., 2026).
- **Coconut shell/husk waste:** processed into ash, charcoal ash, nano-charcoal ash, or fine particles; coconut-derived ash has shown rutting resistance improvements in some studies (Jeffry et al., 2018) and continued research interest.
- **Palm oil fuel ash (POFA) and other agro-industrial ashes:** often explored as mineral filler substitutes and binder stiffening agents in regions with palm oil processing.
- **Olive pomace lignin and other lignin streams:** lignin obtained from agro-waste or pulping operations can partially substitute bitumen or act as modifier (Alobeidyeen et al., 2025).

A broad synthesis of agricultural waste ashes in asphalt binder and mixtures is available in the literature (Fareed, 2020).

3. Why bitumen/asphalt can be a “sink” for agricultural wastes

3.1 Scale advantage and diversion potential

Road construction consumes enormous tonnages of aggregates and fillers, and significant binder mass. Even modest replacement fractions can divert large amounts of residues from burning/landfilling. Unlike niche bioproduct markets, roads provide continuous demand where policies and procurement frameworks exist.

3.2 Engineering “tolerance” through mixture design

Asphalt mixtures are composite materials. Performance can be tuned by gradation, binder grade, modifier dosage, and additives (anti-stripping agents, fibers). This allows incorporating wastes with variability, provided characterization and QC are robust.

3.3 Performance co-benefits

Many residues introduce:

- **Mineral effects** (silica-rich ashes act as stiffening fillers, improve rutting resistance),
- **Adsorption effects** (high surface area char/ash adsorbs lighter fractions),
- **Chemical polarity effects** (lignin's polar functional groups can alter binder microstructure),
- **Aging resistance** (certain bio-modifiers influence oxidation pathways).

However, improvements in rutting resistance can come at the cost of low-temperature cracking risk if stiffness rises excessively—highlighting the need for balanced design.

4. Processing routes: from "waste" to "bitumen-compatible" material

4.1 Controlled combustion to produce ash

Ash properties depend strongly on combustion temperature/time and oxygen availability. Over-burning can crystallize silica (reducing reactivity), while under-burning leaves high carbon content, affecting binder demand and moisture susceptibility.

Key parameters:

- Burn temperature (commonly 500–800°C depending on objective)
- Residence time
- Cooling regime
- Grinding and sieving (or ball milling to nano-scale)

Nano-ash approaches have been explored by reducing ash particle size to improve dispersion and interfacial effects (as noted in studies discussed in the agricultural waste ash literature).

4.2 Pyrolysis and hydrothermal routes to biochar and bio-oil

Pyrolysis yields:

- **Biochar** (solid, porous carbon)
- **Bio-oil** (liquid rich in oxygenated organics)
- **Syngas**

Bio-oil can act as a viscosity reducer/rejuvenator in some binder systems, improving low-temperature or fatigue performance but potentially reducing high-temperature stiffness if overdosed (Al-Khateeb et al., 2024).

4.3 Extraction/fractionation to lignin and lignin-based bio-binders

Lignin from agro-waste streams (e.g., olive pomace lignin) or industrial lignin can be blended with bitumen or processed into lignin-based bio-binders. Recent studies continue to evaluate feasibility, performance, and environmental criteria (Hu et al., 2025; Kuksova et al., 2025).

5. Agricultural waste ashes in asphalt: current status and performance trends

Agricultural waste ashes are used in two main ways:

1. **As mineral filler replacement** in asphalt mixtures, and/or
2. **As binder modifier** blended into bitumen (sometimes at micro/nano scale).

5.1 Rice husk ash (RHA)

RHA is silica rich and can stiffen binders. A notable study combined RHA with bio-oil to balance high-temperature performance with low-temperature and fatigue improvements (Han et al., 2017).

Observed trends (generalized):

- Increased softening point and reduced penetration with RHA → higher stiffness.
- Improved rutting resistance if dispersion is adequate.
- Potential workability issues at high dosages without viscosity reducer.
- Moisture susceptibility depends on ash carbon content and surface chemistry.

5.2 Sugarcane bagasse ash (SBA/SCBA)

Recent experimental studies show continuing interest in using bagasse ash as sustainable filler replacement (Šimun et al., 2023; Hipólito et al., 2024; Sarir et al., 2025; Imoh et al., 2026).

Commonly reported outcomes:

- Comparable or improved Marshall stability within an optimum replacement range.
- Potential improvements in stiffness/rutting resistance due to mineral filler effect.
- Need to optimize filler content and binder content due to altered surface area and absorption.
- Quality control critical because bagasse ash composition varies with combustion conditions and contamination.

5.3 Coconut shell ash / coconut charcoal ash / nano-coconut ash

Nanocharcoal coconut-shell ash has been reported to enhance rutting resistance and physical/rheological properties, attributed to high surface area and stronger interfacial forces (Jeffry et al., 2018).

Additional recent/ongoing studies evaluate coconut-based waste as bitumen modifiers or mixture constituents (e.g., coconut shell ash optimization studies).

5.4 Cross-cutting synthesis of agricultural ash in asphalt

A comprehensive review has summarized multiple agricultural waste ashes (RHA, POFA, bagasse ash, coconut waste, etc.) and their influence on binder and mixture performance (Fareed, 2020).

6. Lignin and bio-bitumen approaches: partial substitution of petroleum bitumen

6.1 Why lignin?

Lignin is the second most abundant biopolymer and is available from agro-industrial streams. Its aromatic structure and polarity make it a candidate to partially replace bitumen or act as a functional modifier.

6.2 Performance findings and current evidence

Recent research continues to characterize lignin-based bio-binders and their feasibility as partial substitutes (Hu et al., 2025) and reviews lignin use in asphalt systems (Kuksova et al., 2025).
A study on olive pomace lignin highlights agricultural-waste-derived lignin as an eco-friendly asphalt binder modifier.

Open-access work also reports that increasing lignin content can raise rutting resistance, while excessive dosages may reduce ductility (Pasandín et al., 2025).

6.3 Environmental criteria and LCA signals

Work comparing lignin-modified bitumen and organic bitumen variants suggests that climate impacts may be reduced for certain bio-bitumen options, though trade-offs (e.g., land use/resource consumption) may occur depending on biomass sourcing and processing (Kamratowsky et al., 2026).

7. Biomass-derived bio-oils and rejuvenators in bitumen systems

Bio-oils can be derived from agricultural residues and used as:

- **Rejuvenators** for aged binders (restoring maltenes balance),
- **Viscosity reducers** to improve workability of stiffened ash-modified binders, or
- **Partial bio-binders** in tailored formulations.

A state-of-the-art review indicates bio-oils may enhance low-temperature performance and aging resistance, but effects on high-temperature properties depend on feedstock and preparation method (Al-Khateeb et al., 2024).

The combined RHA + bio-oil strategy in binder design exemplifies a balancing approach: ash improves high-temperature performance; bio-oil improves low-temperature/fatigue performance (Han et al., 2017).

8. Mechanisms of interaction: how agricultural residues modify binder/mix behavior

8.1 Physical filling and densification

Fine ash particles fill voids, improve mastic stiffness, and can reduce binder drainage in some mixes. The particle size distribution, angularity, and specific surface area influence optimum binder content.

8.2 Adsorption and microstructural changes

Porous carbonaceous fractions in ash/biochar can adsorb lighter bitumen components, increasing stiffness and altering viscoelastic response. Nano-scale ash/char can amplify this due to high surface area (Jeffry et al., 2018).

8.3 Chemical functional groups and polarity

Lignin and some bio-oils introduce oxygenated functional groups that can change binder microstructure, compatibility, and aging pathways. Performance depends on blending temperature, shear energy, and storage stability.

8.4 Moisture susceptibility interactions

Ash chemistry and unburnt carbon content can affect adhesion between binder and aggregates. Some ashes may increase stripping risk without anti-stripping additives; others may improve adhesion if surface chemistry is favorable. Rigorous moisture sensitivity testing (e.g., TSR) is recommended for each residue source.

9. Characterization and testing toolkit for the “bitumen technique”

A publishable research program and practical deployment typically require:

9.1 Feedstock and additive characterization

- Particle size distribution (laser diffraction), morphology (SEM)
- Chemical composition (XRF), mineral phases (XRD)
- Surface area (BET) for biochar/nano-ash
- Functional groups (FTIR) for lignin/bio-oil systems

Studies on bagasse ash fillers commonly employ SEM/EDX/FTIR to understand composition and interaction.

9.2 Binder tests

- Penetration, softening point, viscosity
- Dynamic Shear Rheometer (rutting/fatigue indicators)
- BBR / low-temperature performance (where applicable)
- Aging simulations (RTFO, PAV) and aging indices
- Storage stability (phase separation risk for lignin/bio-oil blends)

9.3 Mixture tests

- Marshall stability/flow (for legacy design contexts)
- Wheel tracking / rut depth
- Indirect tensile strength and moisture susceptibility (TSR)
- Fatigue tests (4-point bending where possible)
- Volumetrics: air voids, VMA, VFA

Recent bagasse ash studies include laboratory performance evaluation under such frameworks.

10. Practical mixture design guidance (engineering lens)

Below is a field-oriented framework (generalizable) for deploying agricultural residues in asphalt.

10.1 Residue selection and pre-qualification

1. Ensure consistent supply (seasonality, moisture control).
2. Define processing route (controlled burn vs pyrolysis vs extraction).
3. Establish acceptance criteria: LOI (loss on ignition), fineness, silica content, contaminants (chlorides, sulfates), and moisture.
4. Conduct baseline performance with conventional mix to define target improvements.

10.2 Dosage optimization

Most studies indicate “optimum ranges” rather than linear benefits. Over-dosage can cause:

- Excessive stiffness (cracking risk)
- Workability loss
- Increased binder demand
- Higher air voids or compaction difficulties

For example, coconut-based modifier studies often identify an optimum content beyond which properties decline.

10.3 Compatibility and blending

- Use high-shear mixing for ash/biochar dispersions.
- Control blending temperature to avoid bio-oil volatilization or lignin degradation.
- Consider compatibilizers for lignin/bio-oil storage stability if separation occurs.

10.4 Moisture damage mitigation

If TSR or stripping risk is high:

- Add anti-stripping agents (lime, liquid additives)
- Adjust aggregate gradation and binder content
- Ensure ash is properly processed (reduce carbon, control fineness)

11. Environmental and socio-economic implications

11.1 Benefits

- **Residue diversion:** reduces open burning and uncontrolled dumping.
- **Resource conservation:** partial replacement of mineral fillers and/or petroleum bitumen.
- **Potential GHG reduction:** depends on processing energy and transport distances.

11.2 Trade-offs and cautions

- **Processing emissions:** uncontrolled burning to make ash can negate benefits. Controlled combustion/pyrolysis with energy recovery is preferable.
- **Supply chain emissions:** long transport distances can erode climate gains.
- **Sourcing governance:** ensuring residues are true wastes (not displacing soil amendments or animal feed where needed) requires local context.

Recent environmental criteria work comparing bio-bitumen variants underscores that some options may reduce climate impacts, while other impact categories can worsen depending on sourcing (Kamratowsky et al., 2026).

11.3 Circular economy pathways

The bitumen technique can be part of a circular procurement framework: municipalities or highway agencies can specify approved waste-derived fillers/modifiers with verified performance and environmental declarations.

12. Current status: maturity levels by technology pathway

12.1 Agricultural ash as filler replacement (higher maturity)

- Generally compatible with existing hot mix asphalt processes.
- Strong evidence base for certain ashes (RHA, bagasse ash) but requires local standardization and QC (Fareed, 2020).

12.2 Nano-ash / nano-char (moderate maturity)

- Promising performance (rutting/aging), but nano-processing cost, dust control, and worker safety require attention (Jeffry et al., 2018).

12.3 Lignin-modified and partial bio-bitumen (moderate, rapidly advancing)

- Increasing number of studies and reviews; issues include compatibility, storage stability, and low-temperature ductility at high substitution rates (Kuksova et al., 2025; Pasandín et al., 2025).

12.4 Bio-oil as modifier/rejuvenator (moderate)

- Effective in certain formulations; variability of bio-oil chemistry remains a major challenge (Al-Khateeb et al., 2024).

13. Case examples from the recent literature (illustrative)

13.1 RHA + bio-oil balancing strategy

RHA increased high-temperature performance while bio-oil acted as viscosity reducer and improved low-temperature/anti-fatigue behavior, demonstrating a multi-component design approach (Han et al., 2017).

13.2 Bagasse ash substitution in asphalt mixtures

Multiple studies show feasibility of substituting conventional filler with bagasse ash in controlled proportions, with continued optimization using laboratory and advanced characterization (Šimun et al., 2023; Hipólito et al., 2024; Sarir et al., 2025; Imoh et al., 2026).

13.3 Lignin as partial substitute/modifier with environmental criteria

Studies increasingly couple performance evaluation with LCA-style environmental screening to prevent burden shifting (Kamratowsky et al., 2026).

14. Key challenges limiting scale-up

1. **Feedstock variability:** seasonal and site-specific differences in ash chemistry and carbon content.

2. **Processing standardization:** lack of harmonized protocols for ash/biochar production for asphalt use.
3. **Compatibility/storage stability:** lignin and bio-oil blends can separate or age differently than conventional binders.
4. **Performance trade-offs:** rutting gains may increase cracking risk; moisture susceptibility can rise.
5. **Field validation gap:** many studies remain laboratory-scale; long-term field sections and monitoring are limited.
6. **Policy and specifications:** road agencies require standardized acceptance criteria, EPDs, and performance-based specs.

15. Future perspectives and research roadmap

15.1 Move from "one-factor" to multi-objective optimization

Future work should optimize residue dosage considering rutting, fatigue, thermal cracking, moisture damage, workability, emissions, and cost simultaneously—using response surface methods, machine learning, or performance-based balanced mix design.

15.2 Standardize residue processing and QC

Develop technical standards for:

- permissible LOI range (carbon control),
- minimum fineness and maximum particle size,
- contaminant thresholds,
- certification of controlled combustion/pyrolysis conditions.

15.3 Couple engineering performance with life-cycle sustainability metrics

LCA should be integrated into mixture design and procurement, building on environmental screening approaches in recent bio-bitumen work (Kamratowsky et al., 2026).

15.4 Expand field trials across climates and traffic classes

Long-term monitoring of pilot roads under hot-wet, hot-dry, and cold climates is essential to confirm aging, raveling resistance, and moisture durability.

15.5 Integrate with low-temperature asphalt technologies

Warm mix asphalt, foamed bitumen, and rejuvenator strategies could reduce processing energy and improve the feasibility of stiffer ash-modified systems.

15.6 Develop circular supply chains at district/state level

Especially in residue-rich agricultural regions, decentralized ash/biochar hubs near agro-processing plants can minimize transport emissions and improve consistency, enabling steady supply to nearby road projects.

16. Conclusion

The bitumen technique offers a practical circular-economy pathway for eco-friendly agricultural waste management by transforming residues into functional asphalt fillers and binder modifiers. Evidence indicates that silica-rich ashes (RHA, bagasse ash and others) can improve rutting resistance and sometimes overall mixture performance when processed and dosed correctly, while lignin-based and bio-bitumen options provide a promising route to reduce petroleum dependence. Bio-oils and nano-scale ash/char systems further enable tailored rheology and aging control, but introduce challenges in variability, compatibility, moisture susceptibility, and long-term durability. The next phase of progress should focus on standardized processing, performance-based specifications, robust life-cycle evaluation, and large-scale field demonstrations. If integrated with circular procurement and certified residue supply chains, agricultural waste-modified asphalt could deliver dual benefits: cleaner residue management and more sustainable road infrastructure.

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