



Effect of Agricultural and Industrial Waste Reinforcement Content on the Wear Behaviour of Aluminium Matrix Composites: A Systematic Review

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Abstract: Aluminium matrix composites (AMCs) with agricultural and industrial wastes can provide an alternative way of achieving better tribological properties and waste valorisation at relatively lower cost. However, the influence of the amount of reinforcement on wear is not the same for all types of waste and testing conditions. This systematic review aims to bring together experimental evidence on the effect of reinforcement content on the wear behaviour of waste-reinforced AMCs. The review is done based on the study-selection process reported in the source manuscript, which includes 141 studies found by searching in Scopus, Web of Science, ScienceDirect, SpringerLink and Google Scholar. Evidence was compared based on: origin of waste, reinforcement material, matrix material, processing method, wear-test conditions and reported wear mechanisms. In the evidence base, moderate reinforcement contents typically deliver the best combination of hardness, particle dispersion and interfacial stability, while too much reinforcement can result in agglomeration, porosity and particle pull out. The wear behavior of industrial wastes (especially that of fly ash) is relatively uniform, while that of agricultural wastes (e.g., rice husk ash) varies somewhat depending on the material. Performance can also be further enhanced with hybrid systems, though the apparent benefits of these rely heavily on the composition and processing. In general, the amount of reinforcement used should be a design criterion which depends on the condition being controlled. Future works should harmonize the wear testing procedures and create predictive models with reinforcement characteristics and service conditions.

Keywords: Aluminium Matrix Composite, Agricultural Waste, Industrial Waste, Fly Ash, Rice Husk Ash, Reinforcement Content, Dry Sliding Wear, Tribology, Sustainable Materials.

1. Introduction

Aluminium matrix composites (AMCs) are of great interest in the field of lightweight tribological engineering since they have the potential to combine the low density and processability of Al alloys with the hardness, stiffness and wear resistance of a dispersed reinforcement phase. Synthetic ceramics like silicon carbide, alumina and boron carbide have been extensively used in conventional AMC development. Although these reinforcements can significantly enhance hardness and wear resistance properties, their production and processing are associated with higher material cost and embodied energy, and thus act as an incentive to explore reinforcement options with lower cost and embodied energy (Sahin, 2003; Garg et al., 2019; Razzaq et al., 2021).

The alternative path is from the agricultural and industrial wastes. There are many agro-residues like rice husk ash, sugarcane bagasse ash, ash from coconut shell, ash from bean pod etc. may be rich in silica or other mineral phases, and fly ash, red mud, quarry dust, slag and other industrial wastes may be rich in ceramic or oxide phases which may participate in load transfer and provide surface protection. Their incorporation into aluminium composites are able to solve a materials-performance challenge and a waste-valorisation challenge (Lancaster et al., 2013; Dixit & Suhane, 2022; Dey & Pandey, 2016).

However, the presence of a waste reinforcement cannot be used to determine its tribological value. Reinforcement content affects the number of hard particles or load-bearing particles at the sliding interface, the likelihood of particle-particle contact, continuity of the aluminium matrix and the tendency to defects in the composite. Dispersed particles at low or moderate contents might contribute to increasing hardness, to reducing direct metal-to-counterface contact and to stabilising the wear surface. High levels can cause particle clustering, poor wetting, porosity and debonding of

the interfaces, leading to the generation of loose third body debris and enhanced material removal. Therefore, it does not necessarily mean that a higher reinforcement fraction will result in lower wear.

Such dependence of content is manifested in the literature. Some studies have shown progressive improvement with increase in fly ash or RHA content whereas others show an optimum content of fly ash or RHA and then deterioration. Part of this apparent contradiction is due to the different methods used for the studies; studies vary in matrix alloy, particle size and morphology, the method by which the material is fabricated, the reinforcement chemistry, the load applied, the sliding speed, the sliding distance, the temperature, and the wear test configuration. However, Dinaharan et al. (2023) found that RHA showed beneficial effects in AA6061 at all concentrations (0–8 wt.%) and that the transition from mild to severe wear was affected by the temperature. In the same way, Kumar et al. (2024) found that fly ash of 6 wt. % is the optimum composition in their Al6061/graphite/Mg system for specific test conditions. These results are a good example of the importance of using optimum content in the context of a test envelope, rather than as a material constant.

Another challenge is the use of hybrid systems which are becoming more prevalent. The mixture of agricultural wastes and fly ash or small quantities of synthetic ceramics SiC, B₄C, Al₂O₃ and ZrB₂ are increasingly used. Hybridisation may not only result in a combination of complementary functions (e.g. hard particle load bearing and solid lubrication), but also alter the total ceramic content and the interface structure. Claims of 'synergy' thus should be compared to the matrix alone and to appropriate controls with only one reinforcement.

The source manuscript attempts to remedy this incomplete body of evidence by systematically reviewing the literature that explicitly manipulates the content of reinforcement and reports quantitative measures of wear. The present revision has the same scope and evidence base, but further refines the analytical framework around four questions: (1) What is the trend of wear response as the content of waste reinforcement increases? (2) Are there any systematic differences in the content–wear relationships for agricultural and industrial wastes? (3) What material and test variables account for the disagreements between studies? and (4) What evidence can be used to guide practical optimisation of content for tribological applications?

As such, reinforcement content is not considered an independent predictor in the review, but rather an interacting variable. The overall idea is that the protection by reinforcement and damage by defects compete to control the useful content range. The frame of reference allows the interpretation of the diverse experimental literature, without supposing the existence of a unique optimum for every type of waste, matrix or operating condition.

2. Methods

2.1 Review design and reporting framework

The review was conducted using a process similar to the original systematic review presented in the source manuscript, and was written as reported in the PRISMA 2020 (Page et al., 2021). The aim was to select experimental work where an agricultural or industrial waste was employed as reinforcement in an aluminium matrix with the amount of reinforcement varying sufficiently to allow for their relationship to wear behaviour to be evaluated. The original review protocol included the following: Population: aluminium matrix composites; Intervention: reinforcement using waste materials; Comparison: reinforcement with different combinations of waste; and Outcome: wear behaviour.

2.2 Information sources and search strategy

Scopus, Web of Science, ScienceDirect, SpringerLink and Google Scholar are the sources of searching the manuscripts. The main search concept was a combination of the terms aluminium/aluminum, matrix-composite, agricultural waste, industrial waste, wear, tribology and content/fraction/weight-percent. No year restrictions were made and the search was done in March 2025. A search of the reports produced 577 records. The counts listed here are not replaced with new and invented screening numbers because the present manuscript is a revision of the above cited review and not a new database search.

2.3 Eligibility criteria

The studies were considered acceptable if they tested the dry-sliding or abrasive wear of an aluminium matrix composite reinforced with an agricultural or industrial waste as reinforcement, and the weight or volume fraction of the reinforcement was varied as a controllable variable in the experiment, and quantitative wear data were provided such as wear rate, mass loss or specific wear rate. Peer-reviewed journal articles and entire conference proceedings written in English were eligible. Only reviews, book chapters, studies without synthetic reinforcement, investigations of non-wear properties only or fixed-composition studies (without content variable included in the study) or reports without numerical data for extractable wear were excluded.

2.4 Study selection

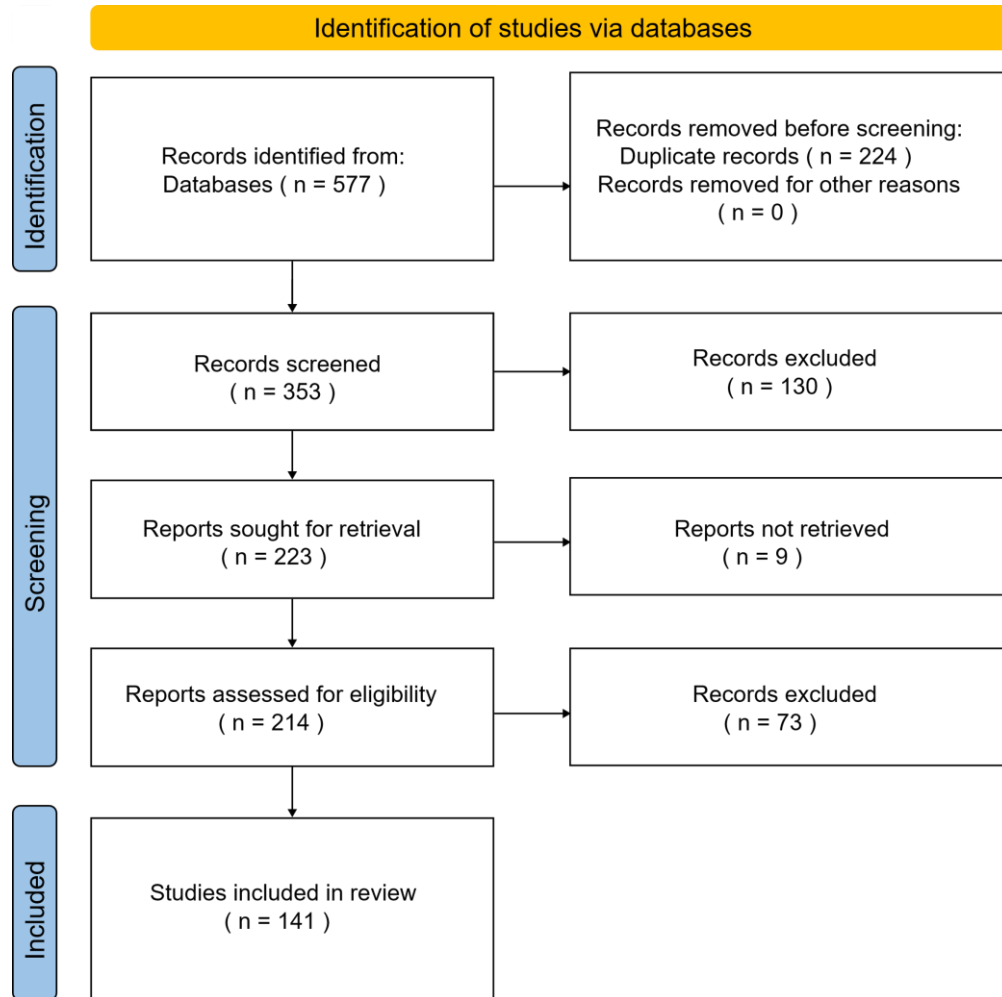


Fig 1. PRISMA flowchart illustrating the study selection process reported in the systematic review.

The reported selection sequence included 577 identified records, 224 duplicates removed, 353 records screened, 130 records excluded at screening, 223 reports sought for retrieval, 9 reports not retrieved, 214 reports assessed for eligibility, 73 reports excluded after full-text assessment and 141 studies included. These values are consistent with each other and have been carried over in the present revision.

2.5 Data extraction and analytical classification

The variables extracted included study identification, matrix alloy, type of reinforcement, reinforcement content, method of fabricating, wear-test configuration and important wear result. In synthesis the evidence was categorized into industrial-waste, agricultural-waste and hybrid reinforcement. As well as being descriptive, this classification is also analytical since the ceramic or oxide fractions are often fairly high in industrial residues, while the ash from agriculture can exhibit more considerable compositional variations associated with the feedstock and combustion and post-treatment. Hybrid systems were considered separately for two reasons: First, mixing wastes together and/or with synthetic ceramics alters the total amount of reinforcement and second, the mechanisms available for wear control are different.

2.6 Quality assessment

The source review was based on a seven-domain checklist adapted to the context of the studies, which included the following: Definition of reinforcement source, explicit control of reinforcement content, wear test standardisation, quantitative reporting of wear, characterisation of wear mechanisms, reporting of test parameters and statistical analysis. Each domain received a score of 0, 1 or 2 and a maximum score of 14 domains was obtained. In the original

review scores of 10 or more were considered high quality and 112/141 studies were in this category. These scores are not intended to be evidence from a validated risk of bias instrument, but rather internal reporting-quality assessment due to the customisation of the checklist.

2.7 Synthesis approach

The synthesis is mostly narrative and comparative due to the use of different matrix alloys, reinforcement chemistries, particle sizes, fabrication processes, counterface materials, loads, sliding speeds, distances, temperatures, and definitions of the wear rates in the studies included. Without a common measurement framework, direct pooling of numerical effect sizes is inappropriate due to these differences. So the analysis emphasizes the direction of the effects, as well as optimum ranges reported, consistency of results between studies, mechanisms of wear and conditions where apparently contradictory results are obtained.

3. Results

3.1 Evidence base characteristics

A total of 141 studies (shown in the original study-characteristics table) is part of the final evidence base. They cover the casting technologies including conventional casting, stir casting, squeeze casting, powder metallurgy, and friction-stir processing and related processes. Aluminium alloys have been the most common evidence represented by AA6061, AA7075, AA2024, A356/LM-series and related alloys and the most common evidence in the case of fly ash and rice husk ash. From a scientific point of view, the resulting heterogeneity is of great importance, as it depends on the content of the reinforcement, on the hardness of the matrix, on the solidification behaviour, on the wetting of the particles and on the stability of the worn surface.

The trend of publication also shows the change from the demonstration of feasibility to optimisation. The source manuscript shows that prior to 2016 there were 36 studies, but it is evident that there was an increase in the number of studies between 2016 and 2020, with the highest number of studies being conducted in 2020 (20 studies) and decreasing but still present after 2020. It is not that they are losing interest, it is rather a trend towards optimisation, hybridisation and tribology for specific applications as the field is maturing from where it was – proof of concept waste incorporation.

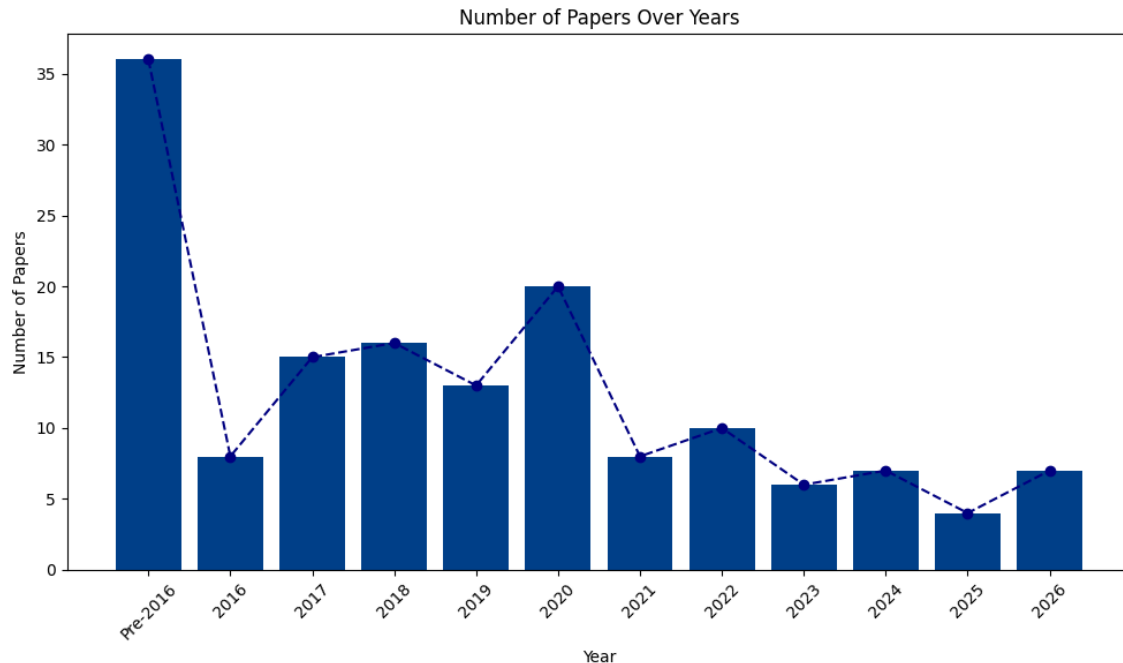


Fig 2. Research trends in the domain of the effect of agricultural and industrial waste reinforcement content on the wear behaviour of aluminium matrix composites.

An additional nuance of interpretation of the temporal pattern in Figure 2 is also important: number of publications is not a measure of evidence quality. The recent literature has been full of highly developed optimisation and

characterisation studies, though there are still some differences in the wear-test conditions that make it difficult to compare studies.

3.2 Characteristics of included studies

The evidence base is also heterogeneous due to the varying waste sources as well as the different experimental definitions of “content” found in each study. Some investigations give only the waste fraction while hybrid investigations give a total reinforcement fraction of which the waste fraction is only a part of the total particulate phase. It is important to keep this distinction in mind when comparing apparent optima. Two different material states are: a matrix with 10 wt.% waste and a matrix with 10 wt.% total reinforcement. Therefore, it is important to keep in mind that comparisons between contents are system-oriented, and not to be interpreted as a common numeric scale.

One way of interpreting the studies included is to make a distinction between composition effects and process effects. In the absence of reinforcement, theory of composition determines the amount of reinforcement that is theoretically available to modify contact while processing determines whether or not the reinforcement is distributed and bonded in a beneficial way. This is significant because there are several studies that compare nominal reinforcement levels between samples produced under different stirring and casting/consolidation conditions. When this occurs, an apparent content effect may be partially due to a change in the dispersion of the particles or in the porosity caused by the process. The review thus takes content as the primary variable of interest and sees processing quality as a moderating variable which is the strength of its expression.

Another significant source of variation is the chemistry of the matrix. There are a number of different aluminium alloys, which vary in hardness, silicon or magnesium level and their heat treatability. The incremental change in a reinforcement fraction may be less significant in a harder alloy, which may still be stabilised by the same reinforcement fraction. Similarly, the compositions of the matrices can affect wetting and interfacial reaction and thus the particle retention during sliding. This implies that the universal optimum reinforcement waste is not applicable for the same waste reinforcement. The most generalizable conclusion is that there is a range of system-specific optimum that is formed by the interaction of matrix, reinforcement and processing conditions.

There's also evidence that shows that wear testing must be used in context with the planned mechanism of service. Abrasive tests focus on resistance to material removal during hard counterbody interaction while dry-sliding tests will also include adhesive transfer as well as oxidation and tribofilm development. A composition which is good for abrasive wear conditions might thus not be in the same order under conditions of adhesive sliding. This difference is significant when comparing agricultural ashes with industrial wastes with a high content of ceramics, as the surface reaction behaviour and particle-fracture behaviour may differ, even if the content of a particular chemical element is the same.

Another source of heterogeneity is the way in which the reinforcement is placed in the matrix. Stir casting and other liquid metallurgy techniques are the most common techniques and hence the evidence presented here is mainly concerned with these methods. But the dispersion quality, wetting, porosity and particle entrapment may fluctuate depending on the melt temperature and stirring intensity and order of adding. This can therefore result in significantly different microstructures for the same nominal reinforcement content, when different studies are involved. This makes it easy to see why it is that some investigations report that the wear resistance is continually improved with increasing content, whereas others report that it deteriorates at high contents. The nominal wt.% is therefore a control parameter, but is not adequate to describe the resulting tribological microstructure.

Additionally, the studies included also vary in their measurements of wear. Pin-on-disc tests are performed with a variety of loads, speeds and sliding distances as are abrasive wear configurations and related dry-sliding configurations. Therefore, a low wear rate in one study does not necessarily mean a low wear rate in another study without taking into account the testing regime. Evidence is best for cases where the reinforcement content has been changed in the same matrix alloy and under the same processing route to minimize the confounding from multiple variable changes. Conversely, cross-comparisons of different alloys and test conditions will be most valuable for the purpose of defining general trends and mechanisms, but not as a general guide to an optimum number.

Table 1: Summary of the Study

Waste category	Representative wastes	Content evidence	Observed wear response	Key moderators
Industrial	Fly ash; red mud; quarry dust; mineral residues	Fly ash commonly performs well at moderate contents; 6 wt.% reported as optimum in one AA6061 study.	Moderate additions commonly reduce wear rate; excessive content can reverse the benefit.	Particle size, porosity, interface quality, load, speed and distance.
Agricultural	Rice husk ash; bean-pod ash; coconut-shell ash; other crop residues	RHA shows favourable responses across roughly 4–15 wt.% depending on material and test conditions.	Wear resistance often improves, but the trend is less consistent than for industrial wastes.	Ash preparation, silica content, particle size, dispersion, temperature and matrix compatibility.
Hybrid waste–waste	Combinations of agricultural and industrial ashes	Commonly investigated at intermediate total reinforcement fractions; optimum ratios are system-specific.	Can combine load-bearing and tribofilm effects, but improvement is not guaranteed.	Total fraction, constituent ratio, matrix alloy, processing route and test severity.
Waste–ceramic hybrid	Waste + SiC, Al ₂ O ₃ , B ₄ C, AlN or related ceramics	Hybrid systems can match or approach synthetic-ceramic-only performance at selected ratios.	Often improved wear resistance relative to the matrix, but the contribution of the waste fraction is difficult to isolate.	Ceramic fraction, particle distribution, load transfer, friction and operating conditions.

3.3 Industrial-waste reinforced AMCs

The biggest and most internally coherent evidence group is industrial waste, particularly fly ash and fly-ash derived cenospheres. In most of the studies, it has been found that additions in the moderate range normally decrease the wear rate as compared to the unreinforced matrix. The mechanism is in agreement with the existence of hard mineral phase which increases load-bearing capacity and decreases the direct aluminium–counterface contact area. The classical studies on fly-ash AMCs showed the feasibility of this route and the subsequent studies took the particle size, load, sliding speed, heat treatment and optimisation aspects in greater details (Rohatgi, 1994; Rohatgi et al., 1997; Ramachandra & Radhakrishna, 2007; Surappa, 2008).

The industrial-waste evidence is also instructive regarding the difference between the content and efficiency of reinforcement. As the fly ash fraction increases, the number of hard particles to carry a contact load increases but the improvement becomes less noticeable because the matrix no longer can achieve uniform dispersion of particles. At that time, the composite may also contain poorly bonded clusters which act as local defects and not as effective reinforcement. The amount of waste added is thus not a measure of the wear response that it will generate, but rather the percentage of particles that are effective in load transfer.

The studies on the industrial wastes also show the significance of the upper limit of the content. When sufficient hard particles are added to a material to hinder matrix deformation there may be reduced tribological benefit in adding additional material. Meanwhile, each added particle will generate one more possible debonding point or local stress concentration point. So, the optimum is the one at which the marginal gain from more load bearing particles is just offset by the marginal loss due to defects and microstructural discontinuity.

For fly ash in particular, the influence of particle morphology must be taken into account, in addition to the particle chemistry. Even fly ash particles that are both generally termed as irregular or angular can exhibit different contact behaviour when compared to spherical or relatively smooth particles. Angular particles can play a major role in abrasive resistance, but can also easily be dislodged and become a third body abrasive. Spherical cenospheres are able to modify the reinforcement population density and packing. These differences justify the more detailed reporting standard, where the ash can be characterised, instead of being considered as one generic waste category.

Another reason for the relative uniformity of the behaviour of industrial residues is the chemical and mineralogical composition of the residues. Fly ash is not a one phase reinforcement; the oxide-rich and aluminosilicate parts of the fly ash could provide the hard phases that will interact with the aluminium matrix and counterface. This complexity

means that two fly ashes with the same nominal additions can exhibit different tribological responses for various reasons such as a different mineralogical composition, particle morphology or processing history. The review thus confirms the use of material descriptors in addition to content, when reporting the wear performance.

Of great practical interest is the fact that the optimum found is frequently different from the highest content tested. It is often found that the optimum wear response is provided at an intermediate addition, not at the highest level of addition. This trend is similar to the simultaneous enhancements of hardness and load sharing versus the agglomeration, porosity or weak interfacial ranges. The outcome is not to be taken as proof that a higher reinforcement is always a bad thing; rather it means that there is an upper and lower limit of the useful range defined by the capacity of the processing route to keep a mechanically continuous matrix.

The most significant finding is that often the relationship between content and wear is non-linear. A number of studies show a minimum wear rate at an intermediate fly-ash content, and deterioration at higher fly ash contents. The deterioration can be reasonably related to particle clustering, higher porosity, poor particle–matrix interfaces and higher generation of free abrasive debris. In the study by Kumar et al (2024), it was found that 6 wt.% fly ash is the optimum composition for the 10 N load; sliding velocity of 3 m/s and a sliding distance of 2 km and that the composition and the load play a significant role in the observed response. The significance of this result is thus limited: the optimum value for this system is 6 wt. % and is only supported experimentally.

Apparent effect of content is complicated by particle size. A greater surface area will be available for a more uniform strengthening if dispersion is realised, while coarse or irregular particles can become stress concentrators or can become separated from the matrix during sliding. It is therefore concluded that an optimum can be considered as an area defined by particle properties, as opposed to a percentage.

The wear mechanism also varies with the type and extent of the wear. Adhesive and mild abrasive processes can dominate at relatively low contents and moderate loads as the aluminium matrix is not covered. With the increase of the reinforcement, the hard particles can provide the contact and favor the formation of abrasive or protective tribolayers. Delamination, particle pull-out, plastic flow and oxidation, however, may be more significant under more severe loads and/or temperatures. Thus, the transition is regulated by the content and operating conditions.

The same general trend (with less extensive evidence) can be seen for other industrial wastes such as red mud, quarry dust, and garnet and related mineral residues. The mineralogy and morphologies have a significant influence on their behaviour. It is thus not possible to carry over the fly-ash optimum directly to all industrial wastes. The content variable should be used together with the chemical composition and structure of particles.

3.4 Hybrid agricultural – industrial, waste – ceramic systems

There is evidence from hybrid reinforcement systems that the maximum wear resistance is not always achieved when one waste is maximised. Various combinations of fly ash with RHA, coconut-shell derived ash, eggshell or other agricultural residues and combinations of wastes with SiC, B₄C, Al₂O₃ or ZrB₂ have been studied to gain multiple functions. Hard phases may be able to bear load and to offer resistance to cutting, and ash-derived silica or carbonaceous phases may influence friction and tribofilm formation.

When hybridisation occurs, the interpretation of content will have to change as different mechanisms of reinforcement by the two phases may be involved. This may be either a relatively hard ceramic that can act as a direct load bearing material and abrasion resistant material, or a waste ash that may affect the transfer film formation or affect the hardness and morphology of the contact surface. The effect thus can be more than a mere average of the individual reinforcements. But this synergy can only be attributed when the contribution of each phase of the experiment can be separated in the experimental design.

Hybrid studies have as their primary analytical value the fact that multiple variables are changing at the same time. The amount of reinforcement, the waste to ceramic ratio and in some cases the particle size may be changed simultaneously in research. In such circumstances, it is not possible to confidently claim that a reported optimum is due to a specific constituent. The evidence is more informative if the total reinforcement is constant but the constituent ratio is varied or if in a sequential comparison the matrix, single-reinforcement systems and the final hybrid composition are included.

Best hybrid designs are those that offer a distinct control sequence. The matrix alone is used as baseline, each single reinforcement system is shown to demonstrate the independent contribution of its component, and the hybrid composition indicates whether or not an additional advantage is provided by the combined system. In the absence of this sequence, the term “synergistic effect” can be used as a descriptive term not as a mechanism demonstrated. Hybrid improvements are thus interpreted with caution and studies separating the contribution of the various constituents are given greater weight.

Furthermore, there is a compositional limit to the extent that hybridisation may become counterproductive. An increase in the total particulate portion can increase the hardness and at the same time reduce the continuous metal area for strain. When sliding, this decreased matrix continuity can lead to particle pull-out and/or crack initiation. Hence, an optimum hybrid composition should be considered as a compromise between the reinforcing capability of the hard phases and the integrity of the matrix in a cyclic contact situation.

The hybrid literature recommends that in engineering design the task should be to maximize complementary functions and not hardness. The composition can cause high hardness, but low toughness or poor particle bonding and/or high porosity. A balanced hybrid by contrast, will provide sufficient matrix continuity and sufficient hard particulate material to provide resistance to plastic deformation and abrasion. The balance is important to consider especially if the component to be tested is required to withstand repeated contact, rather than a one-off wear test in the laboratory.

Interpretation of the hybrid evidence is still to be done with caution, however. A reported improvement can be due to the amount of reinforcement fraction, to a certain composition ratio of the constituents, to a synthetic ceramic, or a change in the processing of the matrix. The correct comparator is thus not just 'hybrid versus unreinforced' but hybrid versus each of the different single-reinforcement compositions at similar total content and test conditions.

Typically, hybrid systems within the source table have full reinforcement ranges of about 6-20 wt. %, though this may vary greatly depending on the system. Study-level evidence also suggests that some systems are dominated by the applied load, the sliding speed and sliding distance. Thus, statistical optimisation may be used to obtain the best combination of experiments without the need to find a transferable material law.

The recent work shows the ongoing trend of moving towards multi-variable optimisation. Sagayaraj et al. (2026) studied AA8079 reinforced with fly ash and AlN ranging from 3–12 wt.% total reinforcement with different loads and sliding speeds which further highlighted the fact that the reinforcement content needs to be considered in conjunction with the operating conditions. The source evidence also covers optimisation of SiC/B₄C/fly-ash composites by RSM, which demonstrates that variation of the synthetic-ceramic fraction can lead to variation of the wear response, without any change in the waste fraction.

3.5 Agricultural-waste reinforced AMCs

The most salient agricultural wastes in the evidence base are rice husk ash. The overall answer is good, but the content effect is not as consistent as the simplified answer: 'the higher the RHA content, the better the wear resistance' would suggest. The silica-rich phases of RHA are considered to have a good performance but it is dependent on ash preparation, particle size, crystallinity, surface treatment, dispersion and matrix compatibility (Dixit & Suhane, 2022).

From the agricultural-waste evidence, it may be concluded that the process of preparing ash is an important issue in the problem of the reinforcement-content. For instance, rice husk ash is formed of silica-rich materials, a large proportion of which is of reinforcing value, but the effectiveness of the reinforcing value depends on the processing and particle condition. Thus, the same nominal wt.% may yield a variety of results as a function of the fineness, morphology, residual carbon or dispersion of the ash. The broad optimal range indicated for RHA is one way to view this; it is not a universal prescription, but rather a response envelope.

Preparation energy is also an important factor contributing to the difference between agricultural and industrial wastes. Agricultural residues in many cases need to be dried, and if necessary, pyrolysed or burnt in a controlled way, and ground, prior to their incorporation into the melt. These can alter the chemistry of the particles and surface state. The tribological performance thus is not only dependent on the type of residue, but also on the process used to transform it to the reinforcement. Two studies that employ the same nominal waste may then be comparing different particle type wastes.

From a practical point of view, this implies that the descriptor for agricultural-waste optimisation should be combined as: waste type, ash condition and reinforcement content. Content alone can determine a maximum for experiments in one preparation route, but cannot be used to define the transferability of content from one processing route to another. This is demonstrated by the RHA evidence as the same general waste type is found in all the various particle sizes, temperatures and fabrication techniques. The optimum thus obtained should therefore be reported as a band depending on preparation of the material and testing environment.

One other common characteristic is the relation between the content of agricultural wastes and the hardness of the matrix. Particulate waste can lead to an increase in hardness and a decrease in tendency to severe plastic deformation of the aluminium matrix during sliding. However, the advantage is only with good adhesion of the matrix to the particulate phase. Poorly bonded particles, once they start to separate can be third bodies in the contact and cause abrasive damage. Therefore, as the content is increased, it is possible to change the wear mechanism from the matrix-controlled deformation to particle-assisted abrasion, if the microstructure is not well consolidated.

Less common agricultural residues confirm the need to report on material-specific basis. However, due to the difference in mineral composition, ash yield, and ash particle morphology it may not be assumed that these bio-derived ashes (bean-pod ash) behave exactly like RHA. Therefore, classification according to “agricultural waste” only works for organising literature, but is not adequate for predicting wear. More of a comparison can be made between specific waste chemistries, processing histories and reinforcement states.

Dinakaran et al. (2023) give a very helpful example as content of RHA and temperature were varied. Wear resistance increased and COF decreased with increase in percentage of RHA (0–8 wt.%) while increase in temperature resulted in reduction in wear resistance and change in wear mechanism. This shows that content of reinforcement can alter the mild and severe wear limits without negating the effect of temperature.

In addition, the newer evidence is extended into the content ranges. Abolusoro et al. (2025) studied the effect of RHA on the wear rate of recycled aluminium alloy at addition level of 5, 10 and 15 wt. % and found that the wear rate reduces gradually with the increase in RHA addition, achieving the lowest wear rate at 15 wt.% of RHA under the reported conditions. Importantly, the same study revealed that the potential for corrosion would be enhanced beyond the 5 wt.% RHA, and thus showed a central conflict: what is optimal for wear did not necessarily prove to be optimal for overall service performance.

The material-specific responses are similar for other agricultural residues other than RHA. The optimum percentage to improve wear behaviour is bean-pod ash, coconut-shell ash, eggshell-derived materials, ash from locust-bean waste, and other ashes. It is, therefore, advisable to consider agricultural waste as a group of chemically heterogeneous reinforcement classes, instead of a class.

Common moderators are particle size and particle surface modification. The fineness of the fine particles can enhance dispersion and interfacial area, but the same time there is risk of creating agglomeration in the case of excessive fineness. Apparent optimum content can be altered by the surface treatment to improve the wetting and the bonding of the interface. These factors account for the reason that different wear rates are reported for studies that use the same nominal reinforcement percentage.

3.6 Cross study synthesis of reinforcement content

The evidence suggests that there are three regimes of reinforcement content. Wear is still heavily influenced by the aluminium matrix in the low content regime, as the reinforcement fraction may be too low to create a continuous load bearing/protective network. Particles are frequently well dispersed and the load is well transferred in the intermediate regime, resulting in the minimum wear rate or coefficient of friction. If the high content regime is used, subsequent additions can cause further formation of agglomerates, generation of porosity, defects at the interface or third body abrasion, resulting in diminishing returns or degradation. Even though not all studies go through all three regimes, the framework has a lot to say about a lot of the non-monotonic behaviour reported.

The three-regime interpretation also helps to reconcile apparently contradictory results. The particulate phase at very low content may not be sufficiently present at the sliding interface in order to affect the sliding interface consistently and the response is still dominated by aluminium matrix. If the particles are numerous enough and well dispersed enough, there is an intermediate range where the particles bear contact loads and they alter the near surface deformation field. Outside of this range, further particles could be added to increase the local stress concentrations or to add clusters and pores that would counter the gains in hardness. It is more convenient than the idea of a single optimum since it provides an explanation of the appearance of various optima in different studies and yet it is physically the same pattern.

The cross-study synthesis results in a practical decision framework. Initially determine the matrix alloy and its inherent hardness and wear behavior. Secondly, characterize the waste reinforcement such that the particle chemistry and morphology is known. Third, choose a content window that includes low, intermediate and relatively high additions instead of trying one addition. Fourth, Content is changed with load, speed, distance and counterface constant. This means that a true turning point can be identified in this design and composition effects can be separated from test severity changes.

Another aspect is replication. If a content level is found to be “optimal” in only one study, the result should not be considered a strong material rule, but rather a local observation. The more the same trend in directions is found in independent investigations with similar matrix alloys and similar test conditions, the more confidence is gained. There is a high level of evidence for the broad mechanisms that apply to several classes of waste, but the numbers that are optimal are less certain, as the experimental space is disjointed.

The evidence base also suggests that there is a difference between lab optimisation and engineering robustness. Under closely controlled conditions, a laboratory formulation can have a very low wear rate; however, a slight alteration in

the dispersion of the particles or quality of the processing can alter the performance. In practice, however, the formulation preferred might be the one that can achieve acceptable wear resistance over a broader range of processing conditions. This focuses attention away from a minimum wear rate to a stable performance around the optimum region.

The framework also proposes that when evidence is heterogeneous, the term “optimal content” be changed to “optimal content range.” Recognition that the range expresses the experimental uncertainty and that small differences between similar nearby contents may not be statistically and/or practically significant. This is particularly significant with waste-derived systems, where there may be more variation in the source than in two different laboratory formulations.

The evidence also shows that the wear rate should be evaluated in combination with the presence of at least one of the mechanistic indicators. To explain the difference in behaviour between two compositions which have similar wear rates, information on coefficient of friction, worn-surface morphology and hardness and evidence for particle pull-out or formation of a tribofilm can be useful. These paired measures provide support to the causal inferences of any content effects and decrease the dependence on a single outcome measure.

It is important to differentiate between extent of the reinforcement-content effect and the direction of the effect. An experimental study might find a lower wear rate as the content is increased, but the actual change may be small compared to that due to load and/or sliding speed. However, with a slight variation in the content, a large response is possible if the test condition is near a so-called "mild to severe" transition point. Content should therefore not be viewed as an individual control parameter of a tribological response surface.

Another synthesis issue relates to the completeness of the reporting. Studies which report only a final wear value, while less informative for revealing content-dependent mechanisms, can be useful for identifying them. The latter can be used to directly observe the location of an optimum or a turning point. This indicates that multiple number of reinforcement levels should be used and evenly spread throughout the anticipated transition zone and not just compare one high content composite to the unreinforced matrix for content studies.

A second cross-study finding is that industrial wastes tend to be more uniformly effective in wear improvements, compared to agricultural wastes. This is not to say that industrial wastes are inherently better. Instead, fly ash has received more attention, and, in many cases, the ceramic phases that form are relatively stable, and the particle size is appropriate for casting. The feedstock and processing variability is higher for agricultural ash, leading to higher between-study variability. Thus, it can be concluded that part of the apparent difference between the category lies in the difference between the material consistency and evidence density.

The third one is that there is not a one-to-one correlation between coefficient of friction and wear rate. If the coefficient of friction is decreased, there is the possibility that the energy dissipated will be decreased, but the wear rate will still be controlled by particle fracture, matrix delamination or third-body abrasion. On the other hand, a compound might have a lower friction and have a better wear resistance. This is significant as tribological optimisation should be defined as the desired outcome and not as friction versus wear.

Lastly, the content of reinforcement is best thought of as an interacting variable. Content, applied load, sliding speed, sliding distance, temperature, particle size, matrix alloy and fabrication route are the most significant factors that predict the wear responses in the evidence base. Without all of these contextual variables, a content value is not very predictive.

4. Discussion

4.1 Principal finding: an optimum is a condition-dependent region, not a universal percentage

Main finding of this review is that waste-reinforcement content has a strong, but not universal effect on AMC wear. The results do not suggest a monotonic relationship in which the higher the percentage of reinforcement, the higher the wear resistance. Many systems, however, show an intermediate performance window where the gains due to dispersion, load transfer and surface protection outweigh the cost of the added interfaces and defects.

The implication is that it is a practical issue: if someone says '10 wt.% is optimum' this should be reported as a system finding. An optimum should be specified as a function of matrix alloy, waste chemistry, particle size, fabrication route, test configuration and test operating severity. Different results can be achieved by the same nominal content, based on the counterface, load or temperature.

This view can alter the way the literature is to be read, based on the condition. Don't take an optimum reported for one material system as a design rule for another alloy or waste without paying attention to the test conditions. Rather, the value is evidence of the fact that the specific system experienced a benign microstructural regime in the vicinity of the

composition. The review thus suggests that the range tested should be reported and that the local trend around the optimum should be reported, rather than giving one percentage value alone.

It also applies to statistical optimisation. These Response-surface or Taguchi approaches can determine the optimum combination of factors that correspond to minimum wear, but the optimum is limited to the region and the state of the materials that were applied in the development of the model. The model may explain variation as content when the content has not been adequately described with respect to one or more of the other factors (such as particle size, load or temperature).

4.2 Differences between industrial and agricultural wastes

This greater consistency in the evidence of industrial waste due to various reasons is probably an indication of material and methodological aspects. Fly ash is frequently composed of hard, aluminosilicate or oxide phases that are not easily deformable and which can have relatively repeatable populations of particles due to its industrial origin. The agricultural ashes are more sensitive to the feedstock and thermal history, which may lead to changes in silica form, residual carbon, alkali content and particle morphology. These differences impact on wetting, dispersion and interfacial bonding. Maturity of evidence is a further explanation. Fly ash has been studied for a longer period of time and in more formulations than have been many agricultural residues. The more often you test, the easier it will be to spot any patterns and determine outliers. In contrast, newer agricultural wastes may have fewer independent studies and their apparent optimum more dependent on the individual experimental choices. The differences in consistency should not be assumed to be a characteristic of the waste alone. The comparison is also important in terms of resources. Supply chains can be relatively stable with industrial residues in the places where thermal power or metallurgical activities are present, while the agricultural residues can be seasonal or geographically diffuse. This has an impact on the reproducibility of reinforcement composition in the production of components. It is therefore reasonable to consider the availability and consistency of material as engineering constraints, as well as tribological performance.

But the supremacy of industrial wastes does not imply a sustainability hierarchy. The benefits of agricultural wastes are their local availability and renewable source as well as decentralised supply chains. They do not have the same consistency across studies which is an engineering issue, but not a reason to exclude them, and can be addressed by normalisation of the preprocessing and characterisation.

4.3 Mechanistic interpretation

Reinforcement may come into play at the sliding interface in a number of ways that may be acting simultaneously. The hard particles will take up part of the contact load and protect the softer aluminium matrix. Detached particles may also create a third body layer whose presence can either decrease the amount of direct metal contact or can be abrasive depending on particle hardness and stability. Under certain conditions, protective films can be formed through oxidation, but the successive pull-out of particles and delamination of the films can result in the exposure of fresh matrix, and hence increase the rate of wear.

The mechanism also depends on the state of the counterface and the third-body layer development. Particles may form at the interface between the surfaces, either as a result of detachment from the surface or as a by-product of the wear of the matrix materials, and for a short time the amount of direct metal-to-metal contact is decreased. In this context the reinforcement content affects the inherent hardness of the composite and the composition and stability of the tribological interface. If the content is changed, therefore, the wear can also change although the bulk hardness changes only slightly. It offers a mechanistic explanation for the common finding of a difference between the behavior of the coefficient of friction and the wear rate.

The surface morphology is an important link between these mechanisms. A worn track with no grooves and no exposed particles is indicative of a different mode of failure than a track with deep grooves and exposed particles. The loads/temperatures dependent transition between these states can account for the variations in results obtained from the same reinforcement at different loads/temperatures. Therefore, the wear surface should be viewed in conjunction with the numerical measure of wear; it should not be used as a stand-alone qualitative observation if microscopy is available.

The bonding between the interface is also of great significance as the reinforcement needs to be coupled to the matrix for long enough to provide load-bearing or surface-modifying effects. The tighter the bond, the better it will hold particles, and the less likely they will pull-out, and the weaker the bond, the more likely the nominal reinforcement will become mobile debris. That is why two composites that have the same reinforcement content can have very different wear rates even when they have the same bulk hardness. Content, then, should not be an end; rather it should be a starting point for a mechanism analysis.

The reviewed evidence is thus best understood as being a competition of mechanisms, rather than a single hardness argument. During the same test, the following mechanisms can be active: load sharing, matrix plasticity, particle fracture, particle pull-out, third-body abrasion and tribofilm development. They vary in significance from one content area to another and depend on the difficulty of the test. A moderate content of composite can be enough to maintain the continuity of the matrix to retain the particles, benefiting from the hardness of the particles. As the content is increased, the likelihood of interparticle contact and weakly bonded regions to control failure increases. Useful content range is the area in which beneficial mechanisms outweigh the damaging mechanisms.

This framework can be applied to service-life. Wear is cumulative and a slight difference in wear rate could have a significant impact on the wear after a long operating period even if it is not significant in a short laboratory wear test. On the other hand, if the composition provides very good performance for a short sliding distance until the transfer layer changes, it may not have such a good sliding property after the change. Thus, long duration testing and repeated cycles are required for laboratory optima to then be converted into laboratory confident component level recommendations.

As a whole, the evidence indicates that reinforcement content can be considered as a design window, which can be coupled with the microstructures and the operating severity. This is in line with the evolution of low-cost fly-ash AMCs as it is known that not only the level of addition, but also the size, shape and structure of the particulates and the condition of the aluminium matrix determine the value of particulate reinforcement (Rohatgi, 1994; Surappa, 2008).

So, increasing the content has two conflicting effects. It makes the occurrence of good reinforcement–counterface interactions more likely, but also leads to a greater number of particles–matrix interfaces where defects can be created. The optimum point is where the benefits of introducing more particles to bear the load are balanced by the damages of introducing more particles, in the form of increased agglomeration, porosity, interfacial damage or abrasive debris.

4.4 Influence of temperature and load

The most important factors to consider are temperature and load which both affect the state of stress and deformation of the matrix. While having reinforcement can still be beneficial overall, the RHA/AA6061 evidence indicates that as the temperature increases, the primary wear process can change to wear by adhesive material flow and severe wear. Likewise, several fly-ash investigations find applied load to be another significant statistical factor affecting wear response. The results show that content optimisation using only room-temperature low-load tests might not apply to service.

Content is modified by load since it dictates the extent to which the applied load can be transferred to the particulate phase without inducing some degree of matrix yielding at the local level. For lower loads, the difference between the compositions can be limited since matrix can take the contact stresses. The well dispersibility of hard reinforcement is more noticeable as the amount of loading increases; on the other hand, imperfections from too much loading are more detrimental. This means the interaction is non-linear - a level that is working well under a certain load may not work as well under a different level of contact pressure.

The parallel interaction is added due to temperature. High temperatures can make the aluminium matrix more susceptible to softening, the change of the stability of oxide or transfer films, and the chance for plastic flow around particles. In such conditions, reinforcement's mechanical function can become more significant, or interface can be more susceptible if bonding between the particles is not strong. The evidence shows a preference that the temperature should be reported as a separate test category, instead of as dry sliding.

4.5 Hybridisation: promise and analytical caution

When the constituents of the hybrid systems function complementary to each other, the hybrid systems will be more effective than single-reinforcement systems. However, in the literature, several variables are often changed at once: total reinforcement, constituent ratio, synthetic-ceramic fraction and processing route. This makes it hard to make causal attributions. Future studies thus should involve equated total reinforcement matched controls and if feasible, a factorial design which would allow separation of the main effects and interactions of each constituent.

An important consideration is that the results of hybridisation should be compared with a matched baseline. When the hybrid has a higher amount of total particulate material than the single-reinforcement comparator, an improvement in wear cannot be claimed as being solely due to the synergy between phases. The more stringent comparison is achieved when the total reinforcement, the processing route and testing conditions are the same, which enables the constituent ratio to be isolated. There are good models of hybridisation in the source evidence, but the literature is not yet sufficient to assume a universal superiority of hybridisation.

Another aspect of design trade-off that arises with hybridisation is the need for complex processes in exchange for performance. Other reinforcement types add more parameters to the mixing and casting process, such as the wetting behaviour of the reinforcement, particle density differences and segregation. Thus, a theoretically attractive composition can be disadvantageous if it cannot be manufactured in a consistent manner in order to achieve the desired microstructure. An optimum material does not necessarily have to be the material that exhibits the lowest wear rate in laboratory tests, but rather that material composition that can be processed at a reasonable cost and achieve the desired wear rate consistently.

4.6 Implications for sustainable materials design

The use of waste-derived AMCs can help towards circular manufacturing by using waste as functional reinforcement, and decrease the reliance on virgin ceramic materials. However, tribological performance is just one aspect of sustainability. Processing energy, ash preparation, transport distance, occupational exposure, corrosion behaviour and recyclability and handling at end-of-life should also be taken into account. The evidence by Abolusoro et al. (2025) was used to demonstrate this trade-off, as higher RHA led to better wear resistance, but corrosion resistance decreased after a lower amount of RHA.

Claims for sustainability, however, should be limited to material processing data. Waste valorisation is helpful if the environmental and economic cost of the process of collection, drying, calcination, milling and conditioning the residue is not greater than the benefit of the use of the waste as reinforcement. Thus, the review also calls for a more comprehensive assessment of sustainability to include tribological performance as well as material preparation and energy use and end-of-life. However, the fact that a waste stream is used as a feedstock does not necessarily make a waste-derived reinforcement sustainable.

There is also a balance that must be struck between the service life and processing burden for a sustainable-material argument. Adding reinforcement may benefit the environment if it significantly lengthens the life of the component, even if it takes energy to prepare the component. On the other hand, if the tribological gain is small, a pre-treatment method that involves a lot of energy may not be warranted. This means that future comparisons will need to be more meaningful combining the life cycle with wear performance rather than waste utilisation as an environmental benefit separately from processing.

The economic feasibility should be taken into the same integrated consideration. Waste reinforcements offer an attractive feedstock cost but this is dependent on the collection, cleaning, drying, milling, calcination and quality-control costs. However, a composition with an excellent laboratory wear rate could be unsuitable for scaling up if it involves a complicated method of preparation. The review thus confirms optimisation on the level of the entire material-production system instead of just composition.

However, for agricultural residues, local availability can still be of great importance. Rice husk, coconut shell or similar wastes can be used as reinforcement, which would help to reduce the transportation and disposal of waste and develop a value-added waste stream in the region where those wastes are plentiful. In some cases, industrial wastes can provide more uniform mineral chemistry, while agricultural residues can provide more robust mineral economy benefits in the local region. Therefore, the engineering decision should take into account the performance as well as the logistics of the waste resource.

4.7 Limitations of the evidence base methodologically

The most significant constraint is for the heterogeneity in the experimental practice. There are a number of different types of wear tests that vary with apparatus, counterface, load, speed, distance, temperature, sample geometry and reporting units. Particle size is not always reported and the characterisation of waste reinforcement by chemical or phase is not always complete. Some studies optimise more than one of the parameters using Taguchi, grey relational analysis or response surface methodology; however, the optimisation results are not directly comparable, if the ranges of the factors are different.

Another limitation is the lack of full reporting of the reinforcement preparation. Many tribological studies report the final wt.%, but do not give much information about ash production, particle classification or surface chemistry. In the absence of such information, however, it is hard to ascertain the true extent of the content effect and whether any apparent effect is indeed due to quantity or to some combination of quantity and particle-state differences. Much more comprehensive reporting of particle morphology, chemical composition and processing history would dramatically facilitate across study synthesis, without necessitating the use of the same material in each study.

This is also true for wear-test nomenclature. The terms ‘wear rate’, ‘specific wear rate’ and ‘weight loss’ are not synonymous. Hence, a direct numerical comparison can be misleading, unless the definition and normalisation of the

metric is obvious. Future studies should report both the raw measurement and the normalised measure, as well as load, sliding distance and velocity, in order to be able to consider the results on a common basis.

The second is that the quality checklist in the review is tailored. It may be helpful to distinguish reporting strength, but should not be thought of as a validated risk-of-bias instrument. The third limitation is that of language and indexing, reported in the source methodology. Lastly, publication bias may lead to positive wear and to successful composite formulations.

4.8 Research priorities

Future research activities should not be based on isolated optimisation studies but on harmonised datasets with mechanistic information. Basic studies should at least include the following information: Reinforcement chemistry, reinforcement phase composition, particle-size distribution, particle morphology, density, porosity, matrix hardness, fabrication parameters, dispersion of reinforcement, counterface material, normal load, sliding speed, sliding distance, temperature, atmosphere and a well-defined wear-rate calculation. It is necessary to impose the obligation to report the unreinforced matrix under the same conditions.

Another research need is independent reproducibility in the lab. Numerous reported optima are from single experimental programmes, and the equipment, specimen preparation and counterface material may differ making comparisons difficult. The repetition of successful compositions under conditions of harmony would help to establish if the trends that have been reported are inherent in the material or specific to a laboratory procedure. This replication would be particularly useful to newer agricultural wastes having a smaller evidence base.

Another focus is improved material-interface level separation. The wear rate is the amount of material removed and coefficient of friction is the resistance to the sliding motion. A stable transfer film can be present without there being any measurable material loss, but with a reduction in friction. For this reason, future investigations should establish the main goal of the system's performance prior to starting the optimisation process. If both outcomes are of interest, then the multi-response approach should be reported and a composition should never be considered optimal based on only one measure.

The evidence also points towards increased awareness of uncertainty of reported optima. Variability in the experimental wear measurements is caused by variations in the preparation of the test specimens, variations in surface finish, variations in dispersion of particles, and repeatability of measurements. Thus for two adjacent reinforcement contents, the difference in their values may not be as significant as indicated by their nominal values. Measurements repeated by different investigators could be reported along with estimates of variability and statistical comparisons which would help to separate real content effects from experimental "noise. This is especially pertinent if recommendations are made for small content intervals.

Finally, translation from material coupon to the engineering component should be considered as a separate validation step. Some parts of the system, like for instance brake-related parts, undergo the changes in contact pressure, temperature and lubrication condition that are not fully reflected in one dry-sliding experiment. The review therefore recommends a staged approach that is: identification of the promising composition under controlled laboratory conditions, followed by testing of the stability of the response under a wider range of operating conditions, and then durability at the component level. This would minimise the potential for transferring a laboratory optimum directly to service without proper validation.

It is also beneficial to report failed or adverse compositions. The upper-content region is of scientific significance since it shows the beginning of the agglomeration, particle pull-out and matrix discontinuity. Reporting these outcomes is important, to ensure that only the 'best performing' formulations are published and to give information to define a realistic processing window. The complete content–wear relationship should therefore include both improvements and deterioration and not terminate at what seems to be the optimum.

A helpful follow-on would be to build up a harmonised content–wear data set with each study sharing the matrix alloy, the waste chemistry, the particle size range, the amount of reinforcement, the full method of fabrication, and the total testing conditions. A dataset similar to this would allow stratified analysis, to determine if material class effects also persist within smaller material classes. It would also help to differentiate true materials trends from artefacts due to the difference in the severity of the experimental measures.

The same should be true for predictive modelling, where uncertainty estimation should be coupled with the modelling. A model that predicts only one optimum wt.% and does not report the confidence intervals has the danger of providing a false sense of precision because the published literature on the experiments is quite heterogeneous. More useful models would be ones that would identify a spectrum of likely high-performance contents and indicate the change of

the spectrum as a function of particle size, matrix alloy, temperature and load. These models would be more readily applied to engineering design than a point recommendation.

More work must be done in the future to enhance the reproducibility of the research by providing a minimum checklist of reporting for waste-reinforced AMC tribology. At least the publications should provide information on waste source and preparation route, chemical or mineralogical characterisation, particle-size distribution, reinforcement fraction, casting or processing parameters, matrix condition, counterface material, load, speed, distance and temperature and wear metric. The evidence base would be strengthened by standardised reporting even if harmonisation of test equipment is not possible.

The development of predictive models of content–wear is another priority. Modelling should take into account wt.% in addition to reinforcement chemistry, particle size, hardness ratio, quality of interface and severity of test to predict wear. There are recent optimisation studies that give valuable experimental data in this direction, but multi-study data sets are desirable before machine-learning or response-surface models can be expected to generalise.

An additional priority is for service-relevant testing. High temperature wear, tribocorrosion, cyclic loading and longer sliding time are still relatively underrepresented. The onset of literature in 2026 also indicates that the field of brake-disc and application-specific tribology is gaining traction, which is beneficial in moving from laboratory optimisation to component validation (Kumar et al., 2026; Dixit & Suhane, 2026).

5. Strengths and Limitations

The main advantage of this review is that it has been explicit about the reinforcement content, in contrast with using a binary variable to represent waste reinforcement. Including 141 studies and keeping the full study-level evidence matrix allows for a wide range of studies to be included to identify common patterns, while retaining material-specific findings. The review also distinguishes between industrial, agricultural and hybrid systems, thus setting up a framework for discussing differences in material consistency and mechanism.

Another strength is the focus on content as a design variable in and of itself. Many of the reviews reviewed waste reinforcements in terms of enhancing the properties of the material, but the present synthesis concentrates on the variation of their performance with reinforcement level. This renders the review more pertinent to the optimisation of compositions and gives an insight into the reasons for different outcomes of studies testing the same waste but within different ranges of waste tested.

The review also has the advantage of being able to include evidence from both the agricultural and industrial sectors, and thus separate general mechanisms from waste specific impacts. This comparative construction minimizes the danger of this one waste type being taken as representative of all wastes, and reveals when a general pattern is broken.

Meanwhile, the synthesis cannot overcome the limitation of the primary studies. The literature is more suitable for the identification of the directionality and the mechanisms of the effects, but they differ in the nature of the specimens, the counterface material, and reporting conventions, so the single pooled effect size is not possible. Conclusions should therefore be interpreted as an engineering guidance based on evidence, rather than as a universal numerical model.

These are mainly limitations that are passed on from the evidence that was used and the original review process. The English language limit might be restricting relevant studies and database indexing and retrieval limits might be causing selection bias. Meta-analysis of magnitudes of wear rate is not possible because of the experimental heterogeneity. Customised quality checklist, which evaluates reporting completeness, but is not a validated risk of bias framework. Finally, a number of studies manipulate more than one variable at a time, which makes it impossible to determine what is the effect of the reinforcement content alone.

6. Conclusion

The results of this review reveal that the amount of reinforcement is one of the significant factors which affect the wear behaviour in agricultural and industrial waste reinforced Al-MMCs depending on the various conditions. Particles addition is often made at moderate concentration in order to balance strengthening and stable particle–matrix contact, but in extreme situations, addition might result in particle agglomeration, porosity and particle loss. The results of industrial wastes, particularly those of the fly ash, are fairly consistent, but the agricultural wastes are more sensitive to their composition and processing conditions. For this reason, an optimum content should be expressed along with the matrix, the particle characteristics, the fabrication route and the wear-test conditions and not as a percentage. Standardised tribological testing, service relevant tribological conditions and predictive content–wear models should be the focus of future research.

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