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Prunus Dulcis (Almond) Shell Powder as a Sustainable Reinforcement for Epoxy Composites: Processing, Properties and Application Potential — A Review

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Abstract — Global almond (Prunus dulcis) production leaves behind a shell fraction that exceeds the mass of the kernel it protects, and the great majority of this lignocellulosic by-product is presently burned, landfilled or sold at low value as biomass fuel. Because the shell is hard, largely cellulosic and available in very large and geographically concentrated volumes wherever almonds are processed, it is a natural candidate for the same role that walnut shell, groundnut shell, coconut shell and rice husk already occupy in the particulate-filled polymer composite literature: a low-cost, renewable, low-density filler for thermosetting resins. This review draws together what is presently known, and what is not yet known, about almond shell powder as a reinforcement for epoxy matrices. It begins with the scale and composition of the waste stream, since both bear directly on whether the material is a viable industrial filler rather than a laboratory curiosity. Processing considerations — drying, size reduction, sieving and surface treatment — are then examined, followed by the mechanical, physical, water-absorption, thermal and morphological behaviour reported for shell-powder-filled epoxy systems, read against the much larger body of work on chemically similar agro-waste fillers where almond-specific data are still sparse. The review closes by identifying the almond shell literature as considerably thinner than that for walnut or coconut shell despite comparable material properties, and names surface treatment optimisation, hybridisation with synthetic or other natural reinforcements, durability under moisture and weathering, and a proper life-cycle assessment against synthetic fillers as the most pressing gaps.

Keywords— almond shell; Prunus dulcis; epoxy composite; agro-waste filler; natural filler; particulate composite; sustainable materials

I. INTRODUCTION

Epoxy resins are used across structural, electrical and coating applications because they cure with low shrinkage, adhere well to a wide range of substrates and can be formulated across a broad range of stiffness and toughness. Left unfilled, however, epoxy is brittle and comparatively expensive, and both properties are usually addressed by adding a particulate or fibrous filler. Synthetic fillers — glass, carbon and mineral particulates — dominate commercial practice, but they carry an embodied energy cost and, for glass and carbon in particular, are not biodegradable at end of life. This has motivated three decades of research into replacing some or all of that synthetic filler content with lignocellulosic agricultural residues: wood flour, rice husk, coconut shell, groundnut shell, walnut shell and a growing list of other shell and husk by-products [1,2].

Almond (Prunus dulcis) is among the most widely cultivated tree nuts, grown at large scale in the Mediterranean basin, Iran, Australia and, above all, California, which accounts for the majority of world production. Processing an almond crop separates the kernel from a hard endocarp shell, and depending on cultivar the shell can represent a substantial fraction of the harvested nut-in-shell mass, so the volume of shell material generated tracks kernel production closely. The present disposal picture is not attractive: shell material is mostly combusted for process heat or electricity, sold as low-value animal bedding, or landfilled, none of which captures the value implicit in a hard, largely cellulosic material available at industrial scale and low cost.

The case for using almond shell as a polymer filler follows the same logic already established for other nut and seed shells. The material is renewable, available at low or negative cost at the point of generation, lower in density than mineral fillers, and abrasion-friendly toward processing equipment relative to harder mineral particulates. Against this, lignocellulosic fillers bring a hydrophilic surface that bonds poorly with a hydrophobic epoxy matrix unless treated, and they introduce moisture sensitivity and, at high loading, embrittlement that mineral or synthetic-fibre systems do not share to the same degree. Whether almond shell filler improves or degrades a given epoxy property is therefore not a fixed fact about the material but a function of particle size, loading fraction, surface treatment and matrix formulation, exactly as it is for the better-studied agro-waste fillers [3,4].

The literature specific to almond shell in a thermosetting matrix is considerably smaller than that for walnut shell, coconut shell or rice husk, despite the shell sharing a broadly similar lignocellulosic composition and hardness with those materials. This review sets out what is available for almond shell specifically, draws on the larger comparable literature where almond-specific results are not yet reported, and is explicit throughout about which statements rest on almond shell data and which are extrapolated from chemically similar fillers. This distinction matters more in a field where the underlying literature base is thin than it would in a more mature one, and it is maintained deliberately throughout the sections that follow.

II. PRUNUS DULCIS: BOTANICAL SOURCE AND WASTE STREAM

The almond fruit is a drupe: an outer hull, a hard woody endocarp (the shell considered here), and the kernel. Commercial processing removes the hull mechanically shortly after harvest and cracks the shell to release the kernel, generating hull, shell and occasional shell-fragment fines as separate by-product streams. Shell morphology and thickness vary by cultivar, with some soft-shell varieties cracking easily and hard-shell varieties requiring more aggressive mechanical action, which in turn affects the particle size distribution obtained from a given cracking process and the amount of fines generated.

Because almond cultivation is geographically concentrated, the shell waste stream is correspondingly concentrated at processing facilities rather than dispersed, which is favourable for an industrial filler supply chain: a single large processor can generate a continuous, compositionally consistent shell stream, in contrast to more dispersed agricultural residues that require aggregation from many small sources. The present low value assigned to the material means feedstock cost for a filler application would be driven primarily by collection, drying and grinding rather than by the raw material itself.

III. COMPOSITION AND PHYSICOCHEMICAL CHARACTERISATION

Almond shell, like other nut and seed shells, is a lignocellulosic material composed principally of cellulose, hemicellulose and lignin, with a smaller extractives fraction and a low ash content. The relative proportions reported across studies of almond and comparable shells vary with cultivar, growing conditions and the analytical method used, and a single precise figure should not be treated as universal; the qualitative picture that matters for composite design is that the material combines a cellulose fraction that confers stiffness with a lignin fraction that confers hardness and dimensional stability, in a rigid cell-wall structure considerably harder than that of bast fibres such as jute or flax [1,12].

Prior to use as a filler, shell material is dried to a low and controlled moisture content, since residual moisture both interferes with epoxy cure chemistry and later contributes to void formation as trapped water evolves during processing or service. The dried shell is then mechanically reduced, typically by hammer milling or ball milling, and sieved to the particle size range wanted for the intended composite; particle size and its distribution are reported consistently across the wider agro-shell literature as first-order variables governing filler dispersion, void content and the resulting mechanical response, and there is no reason to expect almond shell to behave differently in this respect [6,7,8].

Surface treatment is applied for the same reason it is applied to other lignocellulosic fillers: the native shell surface carries hydroxyl groups that make it hydrophilic and chemically incompatible with the non-polar epoxy network, so untreated filler tends to debond from the matrix under load and to absorb moisture in service. Alkali (sodium hydroxide) treatment is the most widely used approach across the agro-waste filler literature generally, acting by removing surface impurities and part of the hemicellulose and lignin, roughening the particle surface and increasing the density of accessible hydroxyl groups available for subsequent coupling. Silane coupling agents, acetylation and benzoylation have all been applied to comparable shell and husk fillers with the shared aim of reducing surface hydrophilicity and improving mechanical interlocking or covalent bonding with the resin. Reported almond-shell-specific treatment studies are limited in number at the time of writing, and treatment protocols validated on walnut shell, groundnut shell or rice husk are the best available guide pending dedicated almond shell studies [10,11].

IV. FABRICATION OF ALMOND SHELL POWDER / EPOXY COMPOSITES

Hand lay-up followed by compression under a light load, and simple compression moulding of a pre-mixed filler–resin paste, are the routes most commonly reported for particulate agro-waste epoxy composites generally, and are the routes almond shell composite studies have followed. Both are attractive for this material system precisely because they require no specialised equipment and tolerate the somewhat irregular particle shape and moderate particle size typical of milled shell powder.

Filler loading is usually expressed as a weight fraction of the total composite and varied across a series of specimens, commonly spanning a range from a few weight percent up to a level — typically somewhere in the range of 20 to 40 wt.% in the comparable shell-powder literature — at which processing becomes difficult because the mix can no longer be wetted out and consolidated without excessive void content. Degassing under vacuum prior to cure is reported as a standard step across the agro-filler literature to reduce entrapped air, which is a particular concern with an irregular, porous particulate filler of the kind milled shell produces [6,8].

Mould release, cure temperature and cure time are generally matched to the epoxy–hardener system's standard cure schedule rather than adjusted for the filler, since the filler itself is thermally passive well below the resin's cure temperature; the exception is where filler moisture has not been adequately removed beforehand, in which case localised boiling and void formation can occur during cure.

V. MECHANICAL BEHAVIOUR

1. General trend with filler loading

Across the broader lignocellulosic particulate-filler literature, and in the more limited almond-shell-specific reports available, a common pattern is described: tensile and flexural strength tend to rise from the unfilled resin over a low-to-moderate filler loading, as the rigid particulate shares load with the matrix and restrains matrix deformation, before falling again at higher loading as particle agglomeration, increased void content and poor stress transfer at debonded interfaces come to dominate. Where the loading range studied does not include this reversal, an apparently monotonic trend in either direction usually reflects that the optimum lies outside the tested range rather than a fundamentally different mechanism [6,7,9].

Hardness and stiffness-related measures generally increase more consistently with filler content than strength does, because a rigid particulate phase raises composite stiffness even where interfacial bonding is too weak to transfer tensile load effectively; this asymmetry between stiffness and strength trends is a recurring and useful diagnostic across the shell-powder composite literature more broadly, and should be expected to hold for almond shell as well [7,8].

Impact strength is the property most sensitive to interfacial quality in this material class. Because impact resistance in a particulate composite depends heavily on the matrix's ability to absorb energy through localised deformation around particles, a poorly bonded, hydrophilic filler surface tends to reduce impact strength relative to the unfilled resin even at loadings where tensile or flexural properties still show a net improvement, which is why impact strength and tensile strength do not always move together across a loading series in this material class [6,9].

2. Effect of particle size and surface treatment

Finer particle size generally improves the strength response at a given loading, because a larger surface area to volume ratio and reduced particle-scale stress concentration both favour more effective load transfer, though very fine particles are also more prone to agglomeration if not adequately dispersed during mixing. Surface treatment, where reported for comparable shell fillers, consistently improves the strength and impact response relative to an untreated filler at the same loading, and is reported to shift the optimum loading for peak strength to a somewhat higher filler content, consistent with improved interfacial load transfer allowing more filler to be usefully incorporated before debonding effects dominate [3,10,11].

Table 1. General mechanical property trends reported for lignocellulosic shell-powder-filled epoxy composites as a function of filler loading and surface treatment

Property	Typical trend with loading (untreated filler)	Effect of surface treatment	Property most sensitive to interfacial quality
Tensile strength	Rises to an optimum, then falls	Optimum loading shifts upward; peak value improves	Moderate
Flexural strength	Rises to an optimum, then falls	Optimum loading shifts upward; peak value improves	Moderate
Impact strength	Often falls even where tensile strength still rises	Improves, but remains the most treatment-sensitive property	High
Hardness / stiffness	Rises more consistently with loading	Modest further improvement	Low
Density	Falls with increasing filler content	Not significantly affected	Not applicable
Water absorption	Rises with increasing filler content	Reduced, but rarely eliminated	High

Trends are drawn from the broader lignocellulosic agro-shell filler literature (walnut, groundnut, coconut shell) and from the limited almond-shell-specific reports available; almond-specific data should be consulted directly wherever precision is required.

VI. PHYSICAL PROPERTIES AND WATER ABSORPTION

Incorporating a lower-density lignocellulosic filler in place of resin volume reduces composite density relative to the neat epoxy, which is part of the appeal of this filler class for weight-sensitive, non-structural applications. Void content generally rises with filler loading in hand-processed particulate composites of this kind, reflecting the greater difficulty of wetting out and consolidating a higher volume fraction of irregular particulate, and void content is a significant confounding variable when comparing strength data across studies that do not report it [6,8].

Water absorption is the physical property most consistently reported to worsen with increasing filler content in this material class, because the cellulose and hemicellulose fractions of the shell are hydrophilic and provide a pathway for moisture uptake at the filler–matrix interface, particularly where that interface is already compromised by poor bonding. Reported water absorption for lignocellulosic-filled epoxy composites generally follows an approximately diffusion-controlled uptake curve toward a saturation level that increases with filler content and decreases with effective surface treatment; almond-shell-specific water absorption data are limited, and this is one of the more straightforward gaps to close given how routine the test is relative to the value of the data it would produce [9,13].

VII. THERMAL BEHAVIOUR

Thermogravimetric analysis of lignocellulosic shell fillers generally shows an initial low-temperature mass loss associated with residual moisture, followed by the principal decomposition of hemicellulose and cellulose over an intermediate temperature range, and a slower, higher-temperature decomposition of lignin extending toward char formation; this staged decomposition is well established for shell and husk materials generally and provides the expected shape of an almond shell thermogram even where almond-specific data are not yet available [13]. Because the filler decomposes at temperatures well below those an epoxy matrix would encounter in cure, but potentially within the range of some service or post-cure heat-treatment conditions, thermal stability of the filler phase is a relevant design consideration for any application involving elevated service temperature.

Differential scanning calorimetry of filled epoxy systems generally shows a shift in glass transition temperature relative to the neat resin that depends on filler loading and interfacial bonding quality, though the direction and magnitude of that shift are not consistent across the wider filled-epoxy literature and should not be assumed a priori for an almond shell system without direct measurement [13].

VIII. MORPHOLOGICAL STUDIES AND INTERFACIAL ADHESION

Scanning electron microscopy of fracture surfaces is the standard method for relating mechanical performance to interfacial quality in this material class. A well-bonded, treated filler typically shows evidence of matrix adhering to the particle surface and, where debonding does occur, a rougher fracture path indicative of energy absorption; a poorly bonded, untreated filler typically shows clean particle pull-out, smooth particle sockets left in the matrix, and visible gaps at the filler–matrix boundary, all of which are diagnostic of interfacial failure rather than matrix or filler fracture [6,7]. Void content and particle agglomeration are also assessed from fracture surface and polished cross-section micrographs, and are the two microstructural features most often invoked to explain a strength decline at high filler loading.

Reported almond-shell-specific micrographs are limited in number, and a systematic fractographic study across a loading and treatment series, of the kind available for walnut and groundnut shell composites, would materially strengthen the mechanistic case for how almond shell filler behaves at the interface [6,7].

Comparison with Other Agro-Waste Shell Powders

Almond shell sits within a family of hard, lignocellulosic nut and seed shell fillers that includes walnut shell, groundnut (peanut) shell, coconut shell and, among husks rather than shells strictly speaking, rice husk. These materials share a broadly similar composition and hardness, and the processing and treatment lessons developed for the better-studied members of this family — walnut and coconut shell in particular — transfer to almond shell with reasonable confidence, since the underlying chemistry and morphology are comparable rather than novel [1,6,7,8,9].

What differs between these fillers in practice is availability and cost structure at a given location, particle morphology after milling, which affects packing and void behaviour, and the specific chemical composition, which affects thermal stability and the fraction of the filler that survives a given surface treatment intact. Almond shell's principal practical advantage over some alternatives is the geographic concentration of supply at processing facilities noted in Section 2, which favours a consistent industrial feedstock; its principal disadvantage as a research subject, at present, is that almond shell has so far been characterised mainly in thermoplastic matrices such as polypropylene [12] rather than in epoxy, so almond-shell/epoxy-specific optimisation work is still largely to be done.

Table 2. Almond shell in the context of comparable agro-waste shell fillers

Filler	Relative hardness	Typical availability	Depth of composite literature	Notes
Almond shell	High	Geographically concentrated at processing sites	Limited	Comparable composition to walnut shell; treatment protocols largely extrapolated
Walnut shell	High	Geographically concentrated	Moderate–extensive	Widely used abrasive and filler material; better characterised
Groundnut (peanut) shell	Moderate	Widely distributed	Moderate	Softer and more fibrous than almond or walnut shell
Coconut shell	High	Concentrated in producing regions	Extensive	One of the best-studied agro-shell fillers
Rice husk	Moderate; high silica content	Very widely distributed	Extensive	Distinct high-silica ash behaviour on combustion

Applications and Sustainability Considerations

The property profile reported for shell-powder-filled epoxy composites generally — reduced density, increased hardness and stiffness at moderate loading, reduced cost, and a renewable filler source — points toward non-structural and semi-structural applications where these trade-offs are acceptable: interior automotive trim and panelling, furniture and decorative panels, low-load housings and enclosures, and packaging or void-fill applications where the composite is not expected to carry significant sustained load or to perform reliably in a wet environment without protective coating [4,5]. The sustainability case for almond shell filler rests on diverting a currently low-value or waste biomass stream into a higher-value application, on the renewability of the feedstock relative to mineral or synthetic fillers, and on the potential to reduce the embodied energy of the resulting composite relative to an equivalent glass- or mineral-filled system. None of these claims has, to the authors' knowledge, been quantified for almond shell specifically through a formal life-cycle assessment; the claim is presently qualitative and by analogy with life-cycle work carried out for other agro-waste-filled composites, and a dedicated almond shell life-cycle assessment, accounting for collection, drying, milling, treatment and composite fabrication energy against the value of the diverted waste stream, would be needed to state it quantitatively [14].

Research Gaps and Future Directions

The almond-specific literature base is thin relative to walnut, coconut and groundnut shell. Many of the processing and treatment conclusions drawn in this review are extrapolated from those better-studied, chemically comparable fillers rather than demonstrated directly for almond shell, and a systematic almond shell study spanning particle size, loading and surface treatment, of the kind already available for several other shell fillers, is the most basic gap to close [6,7,8].

Surface treatment optimisation specific to almond shell has barely been reported. Alkali treatment, silane coupling and combinations of the two are well precedented in the wider agro-filler literature but have not been systematically compared for almond shell, and the treatment that works best for one shell chemistry does not automatically transfer with identical effect to another [10,11].

Hybridisation is essentially unexplored. Combining almond shell powder with a synthetic fibre reinforcement, or with a second natural filler chosen for a complementary property such as a solid lubricant or a different aspect ratio, follows the same logic already productive in other hybrid natural-filler composite systems, but no almond shell hybrid study is known to the authors [15].

Durability under moisture, ultraviolet exposure and thermal cycling is essentially unreported for almond shell composites specifically, despite being the service condition most likely to expose the weaknesses of a lignocellulosic filler in a real application, and despite standard accelerated-ageing protocols already existing for the comparable fibre and shell composite literature [13].

A formal life-cycle assessment comparing almond shell filler against synthetic and mineral alternatives, accounting for the full collection-to-composite energy and emissions balance, has not been carried out for this material and would be needed to move the sustainability argument from qualitative to quantitative [14].

IX. CONCLUSIONS

- Almond (Prunus dulcis) shell is a hard, largely cellulosic agricultural by-product generated in very large volumes at geographically concentrated processing locations, and shares its principal physical and chemical characteristics with the better-studied walnut, groundnut and coconut shell fillers already established in the particulate epoxy composite literature.
- The presently available almond-shell-specific literature is considerably smaller than that for the comparable shell fillers, so much of what can be said about its expected composite behaviour is extrapolated from chemically similar materials rather than demonstrated directly, and this distinction should be kept explicit in any work that draws on this review.
- Mechanical property trends reported for comparable shell-powder epoxy composites, and for almond shell where data exist, follow a rise-then-fall pattern with filler loading for strength properties, a more consistent rise for hardness and stiffness, and a greater sensitivity to interfacial bonding quality for impact strength than for tensile or flexural strength.
- Surface treatment, chiefly alkaline treatment and silane coupling in the wider literature, is expected to improve interfacial bonding and shift the optimum loading for peak strength upward, but almond-shell-specific treatment optimisation has barely been reported and is a priority for future work.
- Water absorption rises with filler content and is the physical property most consistently reported to worsen with the addition of this filler class, which constrains the application space toward components not relying on sustained wet-environment performance without a protective coating.
- The property profile expected of almond shell/epoxy composites points toward non-structural and semi-structural applications — interior trim, panelling, packaging and low-load housings — rather than primary structural use.
- The most consequential gaps are a systematic almond-shell-specific study across particle size, loading and treatment; exploration of hybrid almond shell systems; durability data under moisture and weathering; and a formal life-cycle assessment quantifying the sustainability case that is presently made only qualitatively.

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Conflict of Interest
The authors declare no conflict of interest.

Author Contributions
T. Gopalakrishnan: conceptualisation, literature review, writing — original draft, writing — review and editing, supervision. Boopathi S., B. Niranjan and Mukesh P.M.: literature collection, writing — review and editing.

Data Availability
No new experimental data were generated for this review. All material discussed is drawn from the cited literature.

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