Environmental Aspects of Bioapplications of Sustainable Polymers in Jordan

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Abstract: The growing use of biopolymers has positioned them as sustainable alternatives to conventional petroleum-based plastics. However, biodegradability and origin do not guarantee chemical safety, as contaminants, processing residues, functional additives, and degradation products may introduce significant human and environmental health risks. This review examines the sustainability of biopolymers used in human-contact applications through analytical techniques, with particular emphasis on Jordan's emerging bioeconomy. Jordan possesses abundant renewable feedstocks growing in saline environments, yet a gap remains in determining whether these geochemical stressors impact the feedstock and, thus, the finished biopolymer product. Twelve locally studied polymer systems are evaluated for potential contamination pathways and their fit within life-cycle frameworks. Current studies prioritise equal usability over synthetic plastics across various applications, but developments in trace-element screening of feedstocks, region-specific life-cycle inventory data, and frameworks and regulatory standards, especially for long-term exposure, will confirm holistic sustainability rather than mere degradability.

Keywords: Sustainable polymers, heavy metal contamination, Jordan, life cycle assessment, circular economy.

1. INTRODUCTION

1.1. Significance of Sustainable Polymers

The persistence of petroleum-derived plastics in ecosystems, as micro- and nanoplastics now detectable in the external environment (which are then incorporated into food and thus into human bodies), has accelerated global demand for degradable alternatives. Biopolymers offer lower carbon footprints, improved biocompatibility, and reduced environmental persistence through biodegradation, and their market is projected to reach 5.7 million tonnes by 2029, albeit that remains a small fraction of total plastics production. Interest is particularly strong in pharmaceutical drug delivery, biomedical implants, wound care, and cosmetics, where biodegradable materials can reduce long-term medical waste while improving therapeutic performance. Their adoption is also supported by evolving regulatory frameworks abroad, including the European Green Deal [1, 2].

However, biological origin does not guarantee chemical safety. Natural polymers commonly use plasticisers, crosslinkers, stabilisers, and surfactants to achieve the mechanical and functional properties required for real-world applications, and these additives substantially alter the final toxicological profile (section 4). A concrete example was the application of non-target high-resolution mass spectrometry to 43 bio-based and biodegradable products, detecting over 41,000 chemical features. Approximately 67% of extracts induced baseline cytotoxicity, 42% caused oxidative stress, and 23% showed antiandrogenic activity, indicating a toxicological burden similar to that of conventional plastics, rather than proof of equivalence. Similarly, biodegradable polymer matrices can release incorporated metals, plasticisers, and degradation products during use and disposal, creating exposure pathways that are poorly characterized relative to the structural properties of these materials that have routinely been measured [3].

1.2. Scope and Jordanian Rationale

This review evaluates sustainable polymers used directly in human-contact applications, including but not limited to biomedical and personal care formulations, through studies that applied instrumental analyses, with the aim of assessing not only what these materials can do but also the chemical species they introduce to consumers. Jordan provides the geographic focus as it combines two points of interest that have yet to be connected: a growing interest in biopolymer research amongst academics, who have produced mechanically and functionally sophisticated materials, as well as aridisol soils influencing feedstocks, unlike those which have been studied in Europe and the Americas [4]. Commonly used phosphate fertilisers will also affect said soil, allowing the heavy-metal cargo of the Jordanian reserves to be co-extracted from the rocks and enter soil, irrigation water, and plant tissues, creating a direct pathway from mine to polymer

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feedstock [5]. Unlike previous reviews which emphasise material performance, degradation, or life-cycle metrics, this review integrates biopolymer chemistry, analysis, and applications with contamination pathways in a Jordanian context, which has both a proficient biomedical industry and high plastic pollution, and findings may be relevant to other arid and mineral-rich regions developing biopolymers, where geological conditions may similarly influence polymer safety and sustainability.

National circular economy initiatives, including the UNDP Circular Solutions for Plastic Pollution project, which aims to reduce 5,000 tonnes of plastic waste over five years, make the safety of locally sourced biopolymers an urgent question for their further implementation [6].

This review integrates the aforementioned to identify critical evidence gaps in sustainability and research priorities for safety by combining keywords across academic databases using a narrative synthesis approach. Studies were included if they reported instrumental analysis of a biopolymer system with plausible relevance to Jordanian feedstocks or bioapplications. It synthesises existing literature rather than including an original analysis, where empirical evidence would be required to support proposed hypotheses.

2. BIOPOLYMERS WITH BIOLOGICAL APPLICATIONS

This section does not aim to provide an exhaustive survey of polymer properties. Instead, it examines each system specifically to determine how its interactions with functional additives affect safety.

2.1. Alginate

Alginate is a naturally occurring anionic polysaccharide mainly obtained from brown algae and is commonly used in drug delivery, wound dressings, tissue engineering, biosensors, and aerogel systems due to its biocompatibility, low toxicity, and ability to form 3D networks through ionotropic gelation. Its gel-forming ability stems from the coordination of divalent cations, most commonly Ca^{2+}, with guluronate residues, thereby conferring mechanical stability. This same ionic dependence is its primary safety concern. Conventional Ca^{2+}-crosslinked systems undergo ion exchange under physiological conditions, causing cation leakage and matrix destabilisation, a limitation which motivated the development of a metal-free microfluidic proton-gelation alternative that achieves comparable 5-FU encapsulation but without multivalent crosslinkers at Al-Isra University [8]. In contrast, when calcium was maintained, calcium-alginate aerogels showed little hepatic and renal toxicity immediately after oral administration in animal studies, but alterations in gut microbial composition persisted after treatment, suggesting additional biological effects of prolonged exposure [9].

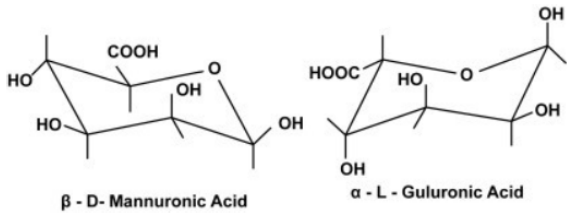

Figure 1: Chemical Structure of Alginate [7].

The Jordan University of Science and Technology has investigated the incorporation of transition metals, such as copper, into alginate/HA aerogels for antibacterial wound dressings, or of ZnO nanoparticles for sustained antimicrobial release, rather than calcium. Functional performance improves significantly (Cu^{2+}-crosslinked aerogels achieved inhibition zones of 36 mm against S. aureus), but matrix dissolution releases Cu^{2+} or Zn^{2+} into tissue [10, 11], both of which have the potential to be cytotoxic at elevated concentrations [12]. If environmental minerals were also absorbed into the feedstock, co-delivery of such incidental elements alongside the intentional Ca^{2+} or Cu^{2+} crosslinking ions represents an unmentioned dual-metal risk.

2.2. Chitosan

Chitosan is a cationic polysaccharide obtained through the partial deacetylation of chitin and is widely investigated for drug delivery, antimicrobial coatings, wound healing, water treatment, and agricultural applications. Its amino groups impart pH-responsive behaviour and strong metal-chelating ability, enabling interactions with negatively charged biomolecules (after the amino groups protonate within stomach acid), metal ions, and other polymers. These same chemical properties are the cause of both its biomedical utility and its relevance to contaminant transport and metal interactions. The same study also showed that, while substituting the nitrogen in low-molecular-weight chitosan improves solubility for surfactant applications, modification of the $–NH_2$ groups (which are responsible for metal chelation) simultaneously alters contaminant-binding behaviour in ways not considered in pharmaceutical applications of modified chitosan [13].

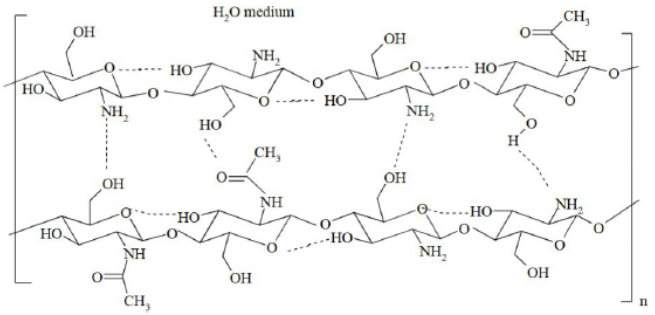

Figure 2: Chemical Structure of Crystalline Chitosan [13].

Jordanian studies have been done on chitosan as nanoparticles in which cisplatin served both as a chemotherapeutic agent and as a functional crosslinker for synergistic doxorubicin delivery, highlighting how platinum incorporation improved therapeutic efficacy, so long as platinum release is controlled [14], as well as as nanocomposites with clay, which achieved complete *P. digitatum* inhibition at 20 μg/mL, but EDX confirmed incorporation of mineral-derived, incidental Mg, Al, and Si, albeit their specific ion release levels over long-term usage was not evaluated [15].

Chitosan's metal-chelating capacity in environmental contexts also plays a pivotal role in the polymer's characterisation. For example, 99.65% removal of the cationic methylene blue was achieved at a capacity of 429.08 mg/g [16]. This creates another circular economy concern: the chitosan becomes metal-laden, so if it is repurposed or landfilled, it becomes a secondary contamination source. In Jordanian agriculture, chitosan demonstrated efficacy as a foliar spray for mitigating saline stress in maize [17], suggesting the potential for redistribution, as the polymer's amino groups would interact not only with beneficial ions but also with trace heavy metals present in irrigation water and soil.

2.3. Hyaluronic Acid

Hyaluronic acid (HA) is a naturally occurring glycosaminoglycan that is made up of repeating D-glucuronic acid and N-acetyl-D-glucosamine units linked via β-(1→3) and β-(1→4) glycosidic bonds. However, it is not of agricultural origin, but endogenously produced in human connective tissue, synovial fluid, the vitreous humour, and the dermal extracellular matrix. HA's endogenous origin gives it intrinsic biocompatibility that other biopolymers lack, but functional modification significantly changes its safety profile. Studies note that whilst there is a preference for its use in non-invasive topical delivery over injectables, especially cosmeceutically for its antioxidant activity, it trades acute injection risk for chronic daily dermal exposure to increasingly complex formulations [19].

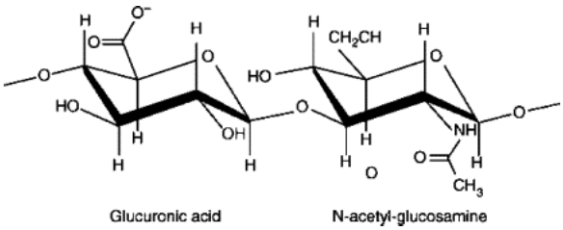

Figure 3: Chemical Structure of Hyaluronic Acid [18].

As for HA's potential as an injectable, Yarmouk University's Fe(III)-EDTA crosslinked HA/κ-carrageenan injectable hydrogel proved that crosslinking with ionic Fe(III) enabled shear-thinning injectability, sustained daunorubicin release over the course of 16 days, and enhanced anticancer activity, whilst the coordination to EDTA is what suppresses free Fe^{3+} Fenton reactions and, thus, production of reactive oxygen species (ROS). Although, as the formulation degrades, *in vivo* pH changes, enzymes, and other ligands competing for the iron moiety will chemically alter Fe(III) in ways not yet defined under biologically realistic conditions, and the enhanced cytotoxicity that resulted may reflect iron-mediated ROS (albeit that is this review's synthesis) [20]. A metal-free alternative was developed by the same facility: a HA/chitosan/glycerophosphate in-situ hydrogel that achieved thermoresponsive gelation at 37°C and has demonstrated significant wound closure in rabbit ischemic models. However, even though it avoids direct metal-ion crosslinking and its associated leakage risks, glycerophosphate introduces phosphate species into the formulation [21], which is especially relevant in a Jordanian context where phosphate-associated trace metals are already present concerns.

2.4. Carrageenan

Carrageenans are a family of anionic, sulfated polysaccharides extracted from red seaweed (Rhodophyta). It is recognised for its capability of gelation and matrix formation, which are related to metal cation coordination, where κ-carrageenan, specifically, gels with K^+, ι-carrageenan with Ca^{2+} [22], and both crosslink with Fe^{3+} in hybrid systems, such as the former with HA (section 2.3). Therefore, it is the most metal-dependent biopolymer reviewed here. Jordanian research groups established carrageenan aerogel microparticles as effective carriers for drugs with low solubility but high permeability. For example, it was analysed using amorphous ibuprofen, as

determined by XRD and DSC, and showed improved dissolution relative to the crystalline counterpart [23]. It was also studied for its capacity to carry meloxicam and atorvastatin, the former of which displayed enhanced dissolution due to de-aggregation within the aerogel's matrix [24]. Moreover, carrageenan-levofloxacin sustained-release tablets demonstrated advantages over the comparator in Wistar rats, as evidenced by pharmacokinetic parameters (e.g., a higher AUC) [25].

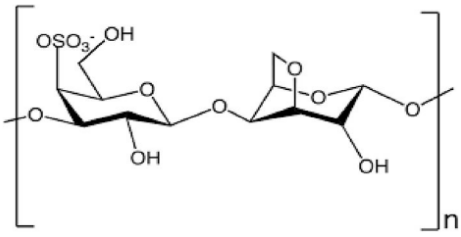

Figure 4: Chemical Structure of κ-carrageenan [22].

Across these systems, the K^+ ions that initiate carrageenan's coil-to-helix conformational transition, which is the main inducer of gelation, remain coordinated in the final formulation's matrix. Furthermore, ion exchange under gastrointestinal conditions, where competing Na^+, H^+, Ca^{2+}, and Mg^{2+} ions are present, could unpredictably alter the gel structure and, therefore, drug release kinetics [26]. Likewise, the anionic sulphate groups that coordinate K^+ may equally coordinate trace heavy metal cations from the feedstocks. Neither the residual ionic content of finished products nor drug release under gastric acidic conditions was characterised.

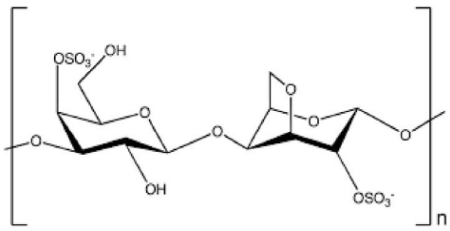

Figure 5: Chemical Structure of ι-carrageenan [22].

2.5. Cellulose

Cellulose is the most abundant biopolymer on Earth, accounting for 40–50% of plant dry weight, and it is chemically comprised of β-D-glucopyranose units linked by β-(1→4) glycosidic bonds in linear, unbranched chains, forming highly ordered crystalline microfibrils through hydrogen bonding, and in turn leading to exceptionally high tensile strength and chemical resistance. In Jordan, specifically, waste from the olive industry is the most well-documented cellulose feedstock, with a nearly 35% cellulose yield from olive pomace via kraft pulping, followed by elemental chlorine-free (ECF) bleaching (section 4.1), and subsequent acetylation [28].

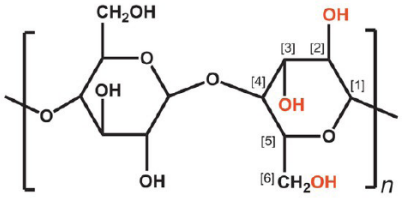

Figure 6: Chemical Structure of Cellulose [27].

Beyond olive feedstocks, Hashemite University studied Jordanian lignocellulosic fibres from olive, lemon, loquat, and palm sources, and confirmed that palm fibre is the top mechanical performer (160 MPa tensile strength, 5 GPa modulus), establishing the biopolymer as comparable to industrially synthesised fibres [29]. Yarmouk University also found a high cellulose content in Dead Sea coast crops (*Peganum harmala*, *Citrullus colocynthis*, *Capparis spinosa*) comparable to biofuel feedstocks [30]. In neither study was contaminant content measured, which is a gap with consequences for any eventual pharmaceutical or food-contact application of cellulose, since these crops are growing in mineral-rich soils where metal bioavailability is amplified by aridisol, low organic matter and high salinity (section 3.2).

2.6. Starch and Cyclodextrins

Starch is a polysaccharide composed of amylose (linear α-(1→4)-linked glucose) and amylopectin (highly

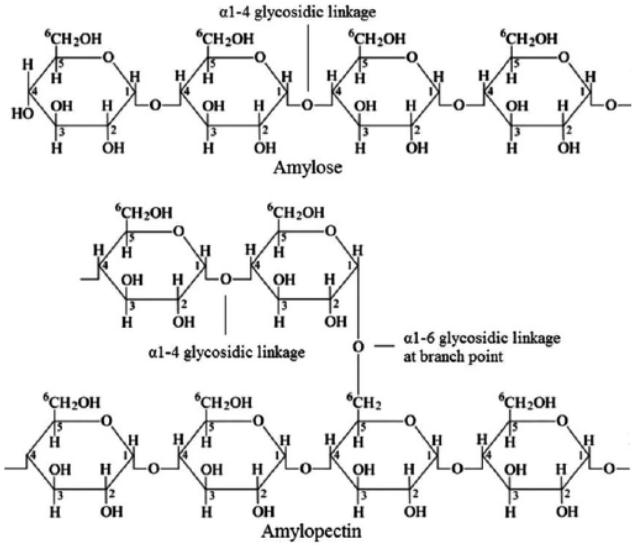

Figure 7: Chemical Structure of Starch [31].

branched with α-(1→6) linkages). It is one of the most commonly used pharmaceutical fillers and disintegrants worldwide and is known for its abundance, as it is extracted from common crops such as potatoes [31].

It may also be applied agriculturally, where starch-borate composites as controlled-release fertiliser coatings have demonstrated improved thermal and mechanical stability [32].

Analytically, boron is a metalloid whose oxide (B_2O_3) and borate ion (BO_3^{3-}) exhibit intermediate metal/non-metal behaviour. While the ion is essential for plants at trace levels and is even used in pharmaceuticals, it is phytotoxic at high concentrations and can accumulate in plant tissues [33].

This leads to the proposed feedback loop, in which metalloid-rich starch-borate coatings applied alongside heavy-metal-dense Jordanian phosphate fertilisers yield successive generations of starch crops with elevated ionic burdens, which, when harvested to produce the next generation of agricultural coatings, systematically amplify contaminant concentrations in both the soil and the biopolymer supply chain—an evidence-based speculation rather than an experimental finding.

Notably, starch also allows for metal coordination via its C2, C3, and C6 hydroxyl groups, albeit they are weaker than chitosan's $–NH_2$ groups, as nitrogen's lower electronegativity relative to oxygen makes amine nitrogen a comparatively softer, more polarisable donor atom, favouring stronger coordination with many transition-metal ions than the hydroxyl oxygens of starch, but overall still relevant at the agricultural feedstock scale when accumulated [34]. However, the literature reviewed does not include studies on starch's metal-binding within Jordanian soil or artificially identical environments, nor on its trace contaminant content when used as a pharmaceutical excipient.

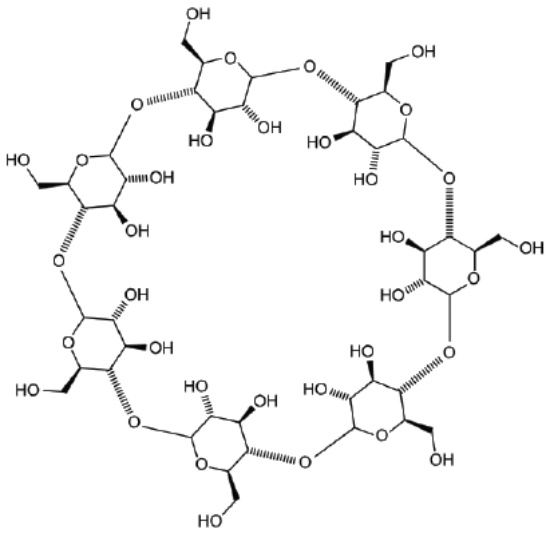

Figure 8: Chemical Structure of β-Cyclodextrin [35].

As for cyclodextrins (CDs), they are cyclic oligosaccharides derived from starch and are widely used in pharmaceutical formulations to improve the solubility, stability, and controlled release of hydrophobic active ingredients through host-guest inclusion complex formation [35].

Crosslinking cyclodextrin molecules yields three-dimensional cyclodextrin-based polymers (CDPs) that exhibit even greater drug-loading capacity and sustained release. This is demonstrated by the Jordan University of Science and Technology, where researchers crosslinked β-cyclodextrin with EDTA dianhydride for 5-FU delivery, thereby improving the aforementioned parameters compared to diphenyl carbonate-crosslinked systems [36]. However, as EDTA is a strong metal chelator, in complex biological environments (e.g. a wound bed where iron from haemorrhage or copper from co-applied wound dressings is present), EDTA-crosslinked CDPs are expected to seize biologically important metals, altering local ion homeostasis beyond intent.

2.7. Polyhydroxyalkanoates (PHA)

Polyhydroxyalkanoates (PHAs) are a family of thermoplastic polyesters synthesised intracellularly by microorganisms to store carbon and energy under low-nutrient conditions. Jordan possesses three resources for PHA production: sesame wastewater, date fruit waste, and Dead Sea water.

They are utilised by the halophilic archaeon *Haloferax mediterranei* to produce the PHA poly(3-hydroxybutyrate-co-3-hydroxyvalerate) (PHBV) with high monomer (3-hydroxyvalerate) molar fractions (18 mol%), providing a PHA source without expensive precursors [38] [39]. It must be noted that such production routes creates a very unique metal exposure profile, as in the latter, for instance, Dead Sea water contains approximately 2.2 M Mg^{2+}, alongside trace Li, Rb, Sr, Ba, and dissolved heavy metals, relevant because *H. mediterranei* can accumulate ionic species intracellularly at exceptionally high concentrations, confirmed by ICP-MS for Li^{+}, Co^{2+}, As^{5+}, and Ni^{2+}, which indicates that the archaeon's metal homeostasis

machinery that can concentrate trace elements within the cell will, by extension, concentrate them within the resultant PHA granules via incidental bioaccumulation, although direct measurements are currently limited [40].

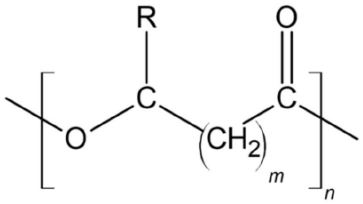

Figure 9: General Chemical Structure of PHAs [37].

2.8. Polylactic Acid

Polylactic acid (PLA) is also a polyester, but it is derived from agriculturally produced lactide (e.g., from corn or sugarcane), which undergoes ring-opening polymerisation. It is the most commercially established biopolymer. PLA literature discusses metal interactions in various Jordanian studies. For example, the Jordan University of Science and Technology investigated functional metal oxide nanoparticle coatings (Al_2O_3, hydroxyapatite, TiO_2) on 3D-printed PLA cortical bone screws, demonstrating that these coatings provided the highest mechanical performance [41, 42]. However, TiO_2 has been documented to have ROS-mediated genotoxic potential under UV or near-UV exposure conditions, and Al_2O_3 coatings raise concerns about aluminium bioavailability, depending on dissolution kinetics in physiological fluids [43, 44], which were not evaluated. In addition to post-implantation, potential exposure may occur during manufacturing, sterilisation, or handling processes.

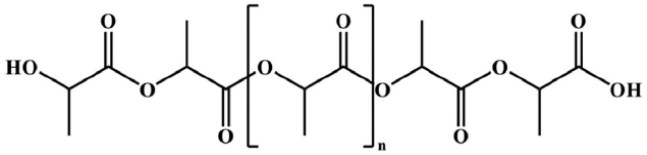

Figure 10: Chemical Structure of Polylactic Acid [41].

End-group functionalisation was found to enable PLA to coordinate with metal ions for stimuli-responsive drug delivery at tumour pH, where the embedded metal is a functional structural component, but system safety depends on its identity (commonly Fe^{3+} or Zn^{2+}), and it impacts coordination stability across biological environments. The literature, however, does not comprehensively examine these complexes across the full range of physiological conditions (e.g., different pHs) [41].

2.9. Polycaprolactone

Polycaprolactone (PCL) is yet another aliphatic polyester widely used biomedically due to its high biocompatibility, ease of processing, and exceptionally slow degradation rate that allows it to persist for two to three years *in vivo*. The latter trait makes it especially suitable for long-term implants, tissue-engineering scaffolds, and highly controlled drug-delivery systems, but it may also prolong the time over which additives or contaminants are released [45].

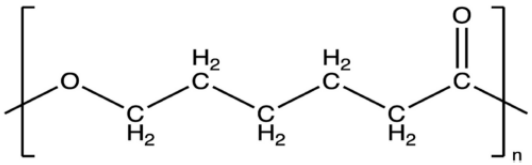

Figure 11: Chemical Structure of Polycaprolactone [45].

For example, Cu(II)-doped hydroxyapatite/PCL nanofibrous membranes have been developed within the region, with large antibacterial inhibition zones and 94.3% catalytic degradation of the carcinogenic, cationic methylene blue in 70 minutes [46]. However, the HAP component raises a local concern: if phosphate precursors used in HAP synthesis carry the trace-metal enrichment characteristic of Jordanian deposits, they may be co-incorporated into the HAP, creating a contamination pathway distinct from Cu^{2+}. Moreover, the long-term (as intended) ion release and its effects under physiological conditions, both for the intended Cu^{2+} and for any co-contaminant metals, were not profiled.

2.10. Gum Arabic (Habeil Gum)

Gum Arabic (GA) is a polysaccharide obtained from *Acacia* species and related trees and shrubs, including *Combretum glutinosum,* found in the Mediterranean region, Africa, and Jordan, which produces Habeil gum. It contains protein fractions that enable adsorption to oil droplets, nanoparticles, and mineral surfaces, making it a valuable emulsifier and stabiliser. It has three molecular fractions (Mw up to 2.06×10^6 g/mol) and especially improved emulsification for a 50/50 Habeil/ Acacia senegal blend [48]. Furthermore, Gum Arabic readily adsorbs onto hydroxyapatite and magnetic nanoparticles, whilst maintaining remarkable stability even under high phosphate concentrations [49].

The study also identified fractions associated with calcium, confirming native coordination to divalent cations via glucuronic acid carboxylate groups, the

same groups that would allow cations from Jordanian soils to coordinate. Elsewhere, Ag nanoparticle-loaded gum Arabic/xanthan cotton bandages were developed with effective antibacterial performance [50], but the especially relevant silver ion release kinetics from the polymer matrix (especially considering GA's proven metal coordination, which would modulate Ag^+ release) were not investigated, even though excessive release can damage healthy mammalian cells.

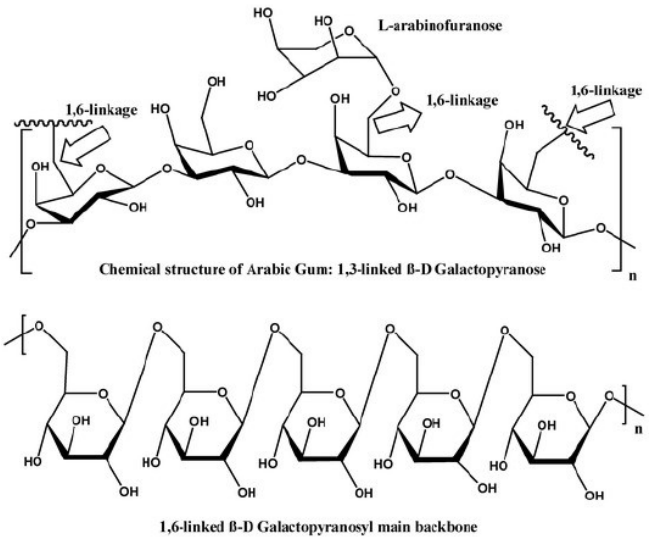

Figure 12: Chemical Structure of Gum Arabic [47].

2.11. Zein

Zein is the main storage protein of corn (*Zea mays*), comprising 50–70% of the total corn endosperm protein. Jordanian zein pharmaceutical research has established that drug release from zein matrix tablets is highly sensitive to ionic strength and co-excipient interactions (e.g., hydrophilic additives in zein coatings can enable controlled release through water penetration and swelling-induced rupture) [52, 53]. These findings have direct implications for metal contamination, as trace cations can alter ionic strength within a swelling zein matrix, thereby modifying the release profile, even unintentionally.

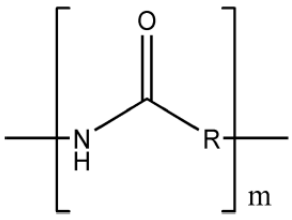

Figure 13: Chemical Structure of Zein [51].

It was independently demonstrated through instrumental analyses that zein's amide, carbonyl, and hydroxyl functional groups electrostatically attract hexavalent chromium with an adsorption capacity of 4.73 mg Cr(VI)/g at pH 2.0 (where the functional groups are protonated within the acidic environment, whereas chromium forms an oxyanion), which, despite having been applied to wastewater, are conditions consistent with the gastric environment in which zein matrix tablets reside during their lag phase [54], thus impacting said environment with how metal-laden the finished product may end up being, depending on the feedstock.

3. JORDANIAN AGRICULTURAL AND INDUSTRIAL RESOURCES

3.1. Flowering of Forestry

To enhance national food security and expand domestic farming, Jordan has actively promoted diverse agricultural scaling strategies, from highly structured urban agriculture initiatives (e.g., rooftop gardening) to optimised irrigation techniques. This expansion is heavily supported by greenhouse farming, especially in the Jordan Valley, which serves as the primary agricultural hub. However, water scarcity remains a limitation to growth, and modern crop management has shifted towards protected greenhouse environments with water-saving practices to achieve self-sufficiency despite only 10% of the country's total land being arable [55, 56].

Using advanced land-use planning and spatial suitability models in Northwest Jordan indicates that 35.6% of the regional land area is potentially suitable for cereal crops and 32.2% for vegetable cultivation. Furthermore, Jordan's National Green Growth Plan (2021-2030) emphasises reclaiming abandoned or marginal lands to expand this agricultural footprint [57] [58]. This is relevant in that Jordan's agricultural biomass, which was confirmed across multiple independent studies in section 2, including olive pomace, date waste, citrus peel, cereal crops, and desert vegetation, is a direct result of this expanding agricultural footprint, and allowing them to enter the path of circularity enables further self-sufficiency.

3.2. A Mineral-Rich Environment

The agricultural context, however, is defined by two soil characteristics that amplify contamination risk relative to temperate comparators. Jordan's dominant aridisol soils have low organic matter (reducing metal chelation capacity), high salt accumulation (promoting competitive displacement of metals from soil-binding

Table 1: Synthesis of the Twelve Reviewed Polymer Systems

Polymer system	Primary Jordanian application	Metal/additive of concern	Classification	Principal evidence gap
Alginate	Wound dressing, drug delivery (5-FU)	Ca^{2+} / Cu^{2+} / Zn^{2+}	Intentional crosslinker	No elemental analysis of feedstock in any Jordanian study was reviewed
Chitosan	Antimicrobial coating, foliar spray	Mg, Al, Si (clay); trace soil metals	Mixed (intentional + incidental)	Metal-laden spent chitosan is an unrecognised secondary contamination source
Hyaluronic acid	Cosmeceuticals, injectable hydrogel	Fe^{3+} (EDTA-chelated)	Intentional crosslinker	Fe(III) speciation under realistic *in vivo* ligand competition undefined
Carrageenan	Sustained-release tablets	K^{+} / Ca^{2+} / Fe^{3+}	Intentional (gelation)	No residual ionic content or gastric-condition release data
Cellulose (olive-derive d)	Fibre, packaging	Feedstock soil metals (untested)	Incidental	No contaminant testing on any Jordanian lignocellulosic source
Starch/cyclo dextrins	Fertiliser coating, excipient	B (borate); feedstock soil metals	Mixed	No Jordanian soil metal-binding or excipient contaminant data
PHA (PHBV)	Biodegradable packaging	Li, Co, As, Ni (bioaccumulated)	Incidental (bioaccumulati on)	No ICP-MS profiling of finished PHA granules
PLA	Bone screws, implants	Ti, Al (oxide coatings)	Intentional coating	ROS/genotoxicity of TiO_2 coating not evaluated under UV *in vivo*
PCL	Long-term implants (2-3 yr)	Cu^{2+} (doped HAP); phosphate trace metals	Mixed	No long-term ion-release profiling under physiological pH 4-5
Gum Arabic (Habeil)	Emulsifier, wound bandage	Ag^{+} (nanoparticle-loa ded)	Intentional dopant	Ag+ release kinetics not measured despite known metal-coordination capacity
Zein	Matrix tablets (controlled release)	Cr(VI) (adsorption capacity, non-Jordanian data)	Incidental (gastric-releva nt)	No Jordanian feedstock trace-metal or gastric-release data
Cyclodextrin -based polymers (CDP)	Fragrance/drug delivery	EDTA-chelated ions (Fe, Cu)	Intentional crosslinker	Local ion-homeostasis disruption in wound beds has not been assessed

sites into the bioavailable soil solution), and limited microbial activity (reducing natural bioremediation) [4]. This means the relationship between total soil metal concentration and the bioavailable fraction cannot be extrapolated from European or North American datasets routinely used as LCA defaults for Jordanian contexts (section 5).

In addition, Jordan holds the world's second-largest phosphate reserves, as previously mentioned. Notably, toxic element concentrations increase from southern mines (Shidyia) toward central/northern mines (Al-Hisa and Al-Abyad), meaning feedstocks sourced from Jordan's primary agricultural zones in the highlands and Jordan Valley (olive, cereal, date, citrus) are most exposed to the phosphate-derived heavy metals documented by ICP-MS. Specifically, U, V, and Hg exceed WHO permissible soil limits, and Cd exceeds ecotoxicity thresholds [5]. Therefore, these metals can be introduced into soil, irrigation water, and plant biomass through bioaccumulation (plant uptake from soil), co-extraction (metals carried with target polymers during purification), and residual contamination (incomplete removal during bleaching or washing). They risk human health, including mercury, a potent neurotoxin that volatilises from heated soils, and cadmium, a Group 1 carcinogen that can accumulate in the kidneys and liver [59].

Dead Sea water is also mineral-rich (34% salinity, $MgCl_2$ levels reaching the upper limit), combined with H. mediterranei's previously mentioned (section 2.7)

intracellular metal accumulation capacity, creates a PHA production environment with no global analogue in terms of ionic complexity [40]. Further in the environment, the Royal Scientific Society of Jordan demonstrated that acid hydrolysis pre-treatment of sesame processing wastewater (HCl 0.4–2.0 M) before fermentation solubilises any metals present in the biomass and carries them into the growth medium, where *H. mediterranei* can concentrate them within PHA granules [39]. This, in addition, provides the salinity context of section 2.5.

3.3. Local Circular Economy Infrastructure

Jordan currently sends over 90% of municipal solid waste (MSW) to landfills. This represents one of the lowest rates of material recovery and recycling in the Middle East and North Africa region, creating a critical baseline problem where even if environmentally superior biopolymers are successfully synthesised from Jordanian feedstocks, end-of-life management infrastructure capable of separating, composting, or recycling these materials does not currently exist on a useful scale. At the municipal level, waste generation in urban centers like Amman averages 0.6 to 1.0 kg per capita daily, with plastics accounting for roughly 13.5% of total MSW and organics comprising the dominant 63% share [60]. Without dedicated separation, these volumes overwhelm existing processing capabilities.

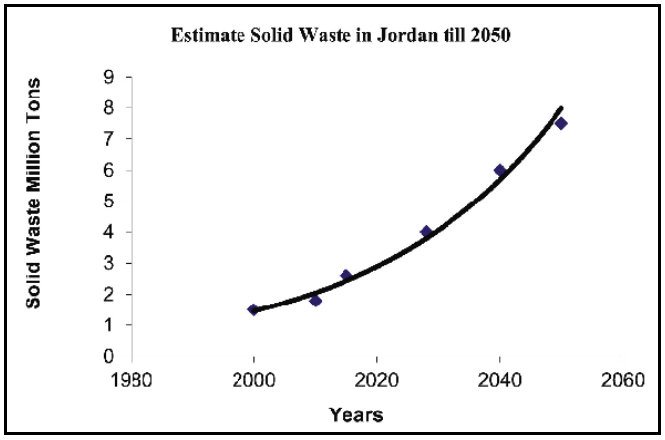

Figure 14: Estimated Solid Waste in Jordan until 2050 [60].

Moreover, the Al-Karak Solid Waste Sorting Plant, Jordan's most well-known material recovery facility, was designed for dry conventional recyclables and lacks mechanisms to identify or separate biodegradable polymers [61]. A PLA food container, chitosan-coated date package, or PHA-based agricultural mulch entering the Al-Karak waste stream would be mixed with conventional plastics, contaminating recycled plastic bales and rendering them unmarketable. Composting has been independently identified as Jordan's most viable organic waste treatment option by Analytic Hierarchy Process (AHP)-based multi-criteria analysis, driven by the ~60% organic fraction of Jordanian MSW [62], and a separate source collection (SSC) pilot in Amman's Al-Radwan district confirmed community participation is achievable with appropriate incentives [63]. An SSC system that specifically includes a category for compostable biopolymers would require minimal additional infrastructure (a dedicated bin colour and collection vehicle) but would prevent contamination of both recycling streams and composting products.

However, composting metal-loaded biopolymers transfers their metal content to compost applied to agricultural soil, directly amplifying the pre-existing mineral burden and creating a feedback loop from waste back to feedstock. This is the central argument of this review: the same circular economy pathway that makes Jordanian biopolymer valorisation attractive also creates a mechanism for concentrating contaminants across successive polymer generations, provided no purification or monitoring steps are inserted. This proposed contamination pathway represents a hypothesis derived from the synthesis of available evidence and should not be interpreted as direct experimental confirmation. This hypothesis is illustrated schematically below.

On the clinical waste side, researchers from the University of Jordan established that Jordanian hospitals generate chemical waste, including materials with high heavy-metal content, and the authors identified the departments producing the most waste, which happen to be the departments where biopolymer-based wound care products and drug delivery systems would most commonly be deployed [64]. Moreover, a general inadequacy in infrastructure across Jordanian healthcare facilities and a lack of staff training in the separation, collection, and treatment of waste lead to haphazard disposal, including open burning or landfilling [65].

Incineration of, for example, silver-nanoparticle-loaded or copper-crosslinked biopolymer waste at insufficient temperatures will generate metal-containing ash and fumes [66], which is an atmospheric exposure pathway that has received no specific attention in either the biomedical polymer or Jordanian waste management literature.

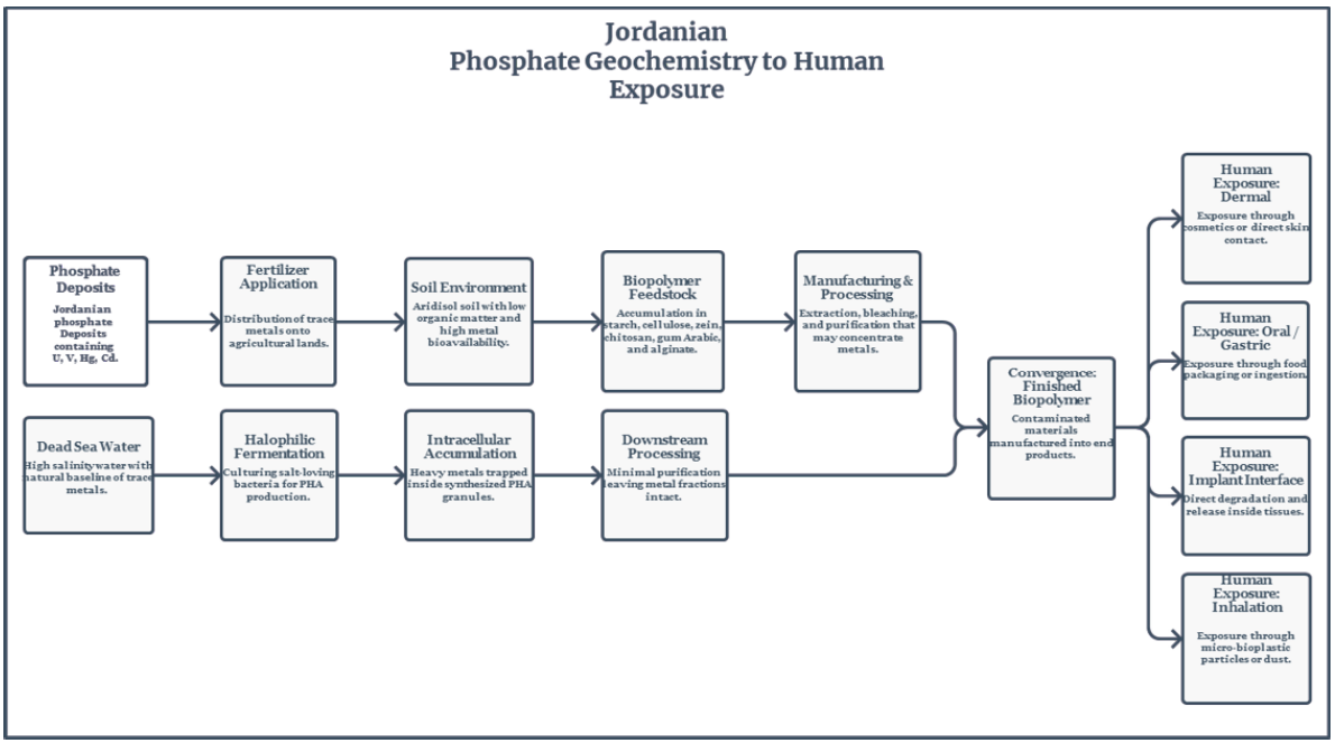

Figure 15: Hypothesised Contamination Pathway from Feedstock to Consumer.

4. SOURCES OF CHEMICAL CONTAMINATION

In addition to the environmental contexts specific to Jordan, which were elaborated upon in section 3, various contamination streams are introduced through industry.

4.1. Processing Contaminants

Catalyst residues: Ring-opening polymerisation of PLA and PCL uses stannous octoate [$Sn(Oct)_2$], and research confirms that while stannous octoate itself is moderately toxic, organotin catalysts (e.g. dibutyltin dilaurate, which is used more so for synthetic polysiloxanes) carry a substantially higher risk of toxicity and bioaccumulation [67, 68]. Beyond tin, transition-metal catalysts (Cu for controlled Atom Transfer Radical Polymerisation, Ru for Ring-Opening Metathesis Polymerisation in β-CD polymer synthesis) leave residues that require rigorous removal before biomedical use [69], which is not demonstrated in any Jordanian study reviewed.

Solvent residues: Kraft pulping uses sodium hydroxide/sodium sulphide (introducing inorganic ions that interact with feedstock metals), cellulose acetate synthesis employs Class 2 solvents like dimethyl acetamide (PDE limits ≈10 mg/day) [28], starch modification may leave acetic/propionic acid residues from anhydride reagents (Class 3, but can interact with pre-existing metal species) [70], and cellulose nanocrystal extraction via sulphuric acid hydrolysis introduces sulphate ester groups while simultaneously solubilising trace metals from the biomass into the hydrolysate [71, 72], all of which creates a processing contaminant problem where reaction temperature and acid concentration, which determine crystallinity and colloidal stability, also govern metal co-extraction efficiency.

Bleaching and purification residues: The ECF bleaching sequence (ClO_2 → cold caustic extraction → NaOCl → H_2O_2) used for olive-waste cellulose can oxidise and precipitate insoluble metals within the pulp, generate adsorbable organic halogens (AOX) via hypochlorite reactions, and trigger radical-generating, polymer-degrading Fenton reactions when hydrogen peroxide reacts with native iron(II) or copper(II) [28]. Chitosan must also be purified via acid/alkali treatment of crustacean shells, followed by decolourisation with oxidising agents ($KMnO_4$ or H_2O_2), which leave manganese or peroxide residues that must be reduced and washed to pharmacopoeial standards [73]. As for calcium-rich alginate, incomplete chemical demineralisation after extraction leaves significant calcium burdens, which are displaced by heavier metals in a competitive process [8].

4.2. Functionalization

4.2.1. Common Additives

Crosslinkers: Glutaraldehyde (GA; TLV 0.05 ppm, mutagenic, probable carcinogen) and epichlorohydrin (ECH; Group 2A carcinogen) provide superior mechanical strength but require extensive purification that is rarely verified to completion. Natural alternatives like citric acid, which is non-toxic, generally recognised as safe (GRAS), but requires temperature optimisation at ~80°C, or genipin derived from gardenia, which is 10,000× less cytotoxic than glutaraldehyde, but is more costly, offer better safety profiles at the cost of more demanding processing [27]. The ionic metal crosslinkers, widely reported in Jordanian literature (Ca^{2+}, Fe^{3+}, Cu^{2+}, K^{+}), are embedded throughout the polymer and released upon degradation, constituting another persistent exposure route (section 2).

Plasticisers: Phthalates (DEHP, DBP, DINP) are restricted worldwide due to established endocrine disruption and reproductive toxicity, but are not banned and thus continue to be used [74]. Even bio-based alternatives (citrate esters, ATBC, glycerol derivatives) have been studied, but they have disadvantages: they migrate from polymer matrices during storage, causing simultaneous mechanical property loss and plasticiser accumulation in surrounding environments. $CaCO_3$ and chitin nanofibrils reduce but do not eliminate ATBC migration from PLA blends [75]. Natural fillers (montmorillonite, halloysite, HAP) can replace plasticisers, too, but introduce various inorganic ions, depending on their geological origins [76]. As for the claim about plasticiser accumulation within the environment, it demonstrated that plasticiser accumulation around polymer fragments can inhibit microbial activity, slowing the biodegradation that is the material's primary sustainability claim [77].

UV stabilisers: TiO_2 and ZnO nanoparticles are especially relevant within Jordan's high-UV arid climate. Under UV, nano-TiO_2 generates ROS with documented genotoxic and ecotoxic effects, whereas ZnO dissolves under acidic conditions ($ZnO + 2H^+ \rightarrow Zn^{2+} + H_2O$), releasing ions at phytotoxic concentrations in Jordanian soil microenvironments (which, despite generally being alkaline due to high calcium carbonate concentrations, plant roots exude organic acids to mobilize nutrients, leading to acidic rhizospheres) [43, 78, 79]. Olive pomace lignin represents a natural UV-stabiliser alternative with genuine Jordanian feedstock availability, but its trace metal content from the soils on which the olive was cultivated is understudied [80, 81].

4.2.2. Modifiers for Tunable Degradation

Biopolymers degrade through several pathways, with the dominant mechanism dictated by chemistry, environment, and application context. Hydrolytic (acid-base) degradation is central for many synthetic and semi-synthetic biodegradable polymers, where water attacks hydrolysable bonds such as esters (e.g., PLA, PHA, PCL), glycosidic linkages (in polysaccharides), and, to a lesser extent, amides (e.g., zein), with rate strongly modulated by pH, ionic strength, and autocatalysis from generated carboxylic acid end groups. In natural environments, biodegradation by microorganisms predominates through extracellular enzymes that progressively cleave polymer chains before mineralisation to CO_2, CH_4, H_2O, and biomass. Photodegradation occurs upon exposure to sunlight or UV sources, where photon absorption generates ROS that trigger chain scission and oxidation, particularly in aromatic or conjugated segments or in the presence of photosensitizers, such as intentional or incidental metal-ion residues and added TiO_2 (section 4.2.1). Redox-driven degradation is increasingly exploited in biomedical contexts, where disulfide-containing crosslinkers or redox-sensitive moieties (intentional or incidental) undergo cleavage in reducing intracellular (e.g., high glutathione) or oxidising extracellular environments, enabling breakdown of hydrogels [82].

Importantly, degradation is not an intrinsically fixed property but can be tuned through design, especially by introducing or modifying functional groups along the backbone, side chains, and chain ends. By varying the density and chemical environment of the aforementioned hydrolysable bonds, it is possible to control both the rate and mechanism of chain scission under different conditions. Post-polymerisation functionalization, such as introducing carboxyl, amine, sulfate, or hydroxyl side groups, or grafting hydrophobic or bulky substituents, can modulate water uptake, enzymatic accessibility, and local pH, adjusting the degradation timescale. End-group engineering (e.g., capping hydroxyl termini or adding acid- or enzyme-labile moieties) further refines degradation profiles by dictating the initiation sites. Recent reviews emphasise that combining such features yields biopolymer systems whose lifetimes can be matched to specific biomedical or packaging applications, minimising accumulation while avoiding toxic degradation byproducts [83, 84].

Incomplete degradation under ambient, rather than controlled industrial, conditions, particularly in Jordan's low-microbial-activity aridisol soils, fragments

biopolymers into micro- and nanoplastic particles that adsorb heavy metals and microbes from surrounding environments, rather than clean water and CO_2. Cytotoxicity of such fragments is driven by their additives rather than base polymer identity. For example, PLA with a higher content of plasticisers and crosslinkers generates significantly higher oxidative stress in lung and liver cell models [85].

Therefore, safety is dictated by concentration, coordinated species, and degradation pathways. Engineered systems (e.g., Fe(III)-EDTA hydrogels, section 2.3) chelate free ions to mitigate oxidative risk, whereas incidental, uncontrolled geogenic contamination provides no functional benefit and introduces unmonitored, unrecognised human exposure, wherein the advanced functionalisation techniques themselves (e.g., nanofiller incorporation [76], polyphenolic antioxidant grafting [77], surface plasma treatment [83], and main-/side-chain chemical modifications [85]) emphasise the importance of evaluating chemical modifications for material performance and long-term safety.

4.3. Extractables and Leachables

Extractables migrate under exaggerated laboratory conditions, while leachables partition into products during normal use. Regulatory control follows elemental-impurity limits such as ICH Q3D, alongside extractables-and-leachables assessment frameworks recommended in pharmacopoeial general chapters (e.g., USP <1663>/<1664>), which together govern permissible daily exposure to process- and container-derived elemental and organic contaminants, but in advanced biopolymer platforms, the material serves simultaneously as the container, matrix, and delivery mechanism, making any released ion (e.g., Ca^{2+}, Fe^{3+}, Cu^{2+}, crosslinker residue, or co-contaminant) an intrinsic leachable by pharmacopoeial definition. Leachables can reduce drug efficacy, alter physical properties, and cause immunological reactions (including pure red cell aplasia from rubber stopper leachates) even at sub-microgram concentrations [86].

In cosmeceutical analyses, researchers identified 35 extractables (including phthalates and cyanide derivatives) from commercial packaging using a solvent-free SPME/Py-GC-MS technique, demonstrating that non-intentionally added substances (NIAS) routinely exceed the declared ingredient lists [74]. For Jordanian biopolymer cosmeceuticals, NIAS may include trace metals from agricultural feedstocks, yet no systematic screening has been performed, and current Jordanian regulatory frameworks do not require it. A further limitation is the lack of long-term weathering and high-salinity extraction media relevant to Jordanian ecology and climate.

5. ANALYTICAL CHEMISTRY APPROACHES

5.1. Metal Analysis Methods

ICP-MS is the reference method for trace elemental quantification, achieving ppt detection for most elements, and can even reach ppq for ^{238}U with appropriate sample preparation (albeit such detection limits are instrument- and matrix-dependent and are rarely achieved in routine biological or polymer matrices without extensive pre-concentration), and is available in multiple Jordanian laboratories [5]. XRF [10] and energy-dispersive X-ray spectroscopy [15, 16, 28, 78] are unsuitable for regulatory-level trace metal screening due to detection levels of 0.1-1%, but retain value for non-destructive spatial elemental mapping of nanoparticle distribution and for initial composite characterisation.

5.2. Organic Contaminant Analysis

Abroad, chromatographic methods coupled to mass spectrometry are routine methods for detecting organic extractables, leachables, residual solvents, additives, and degradation products. GC-MS, including pyrolysis GC-MS (Py-GC-MS) and thermal desorption GC-MS/MS (TD-GC-MS/MS), is particularly suited to volatile and semi-volatile compounds, while LC-MS/MS extends analysis to less volatile or thermally labile contaminants. Solvent-free thermal extraction coupled with Py-GC-MS enables ppb-level detection of cosmetic packaging extractables without introducing additional solvent contamination [74], although background interference can lead to overestimation without appropriate blanks [87]. For polymer-specific characterisation, advanced mass spectrometric techniques have been employed, such as MALDI-MS, ESI-MS, ion mobility MS (IM-MS), and TOF-SIMS, which provide detailed information on polymer architecture, molecular weight distributions, and degradation products that cannot be resolved by conventional GC-MS alone [88]. Complementary chromatographic techniques such as SEC/GPC are widely used to determine molecular weight distributions and monitor polymer degradation, while HPLC-UV remains the dominant approach in regional studies for quantifying known compounds and drug release [28,

39]. However, because UV detection requires prior knowledge of analyte chromophores, it is unsuitable for comprehensive non-targeted contaminant screening.

5.3. Structural Characterisation

Across Jordanian studies, structural characterisation is consistently robust and represents the most mature analytical domain. Spectroscopic methods such as FTIR and NMR are routinely used to confirm functional group modification, polymer interactions, and chemical structure [10, 13, 28]. XRD (including PXRD) evaluates crystallinity and phase transitions, particularly following drug loading or polymer modification [13, 16, 25, 36, 38, 47]. SEM and TEM, frequently combined with EDX, provide information on morphology, particle size, pore structure, and elemental distribution [9-11, 14, 20, 21, 25, 28, 78]. Thermal techniques, including DSC and TGA, assess thermal transitions, crystallinity, and degradation behaviour [13, 20, 25, 29, 36], while BET analysis and nitrogen adsorption porosimetry quantify specific surface area and pore architecture in aerogels and other porous biomaterials [9-11, 16]. Dynamic light scattering and zeta potential measurements are widely applied to nanoparticle formulations to determine particle size distributions and colloidal stability [8, 13, 14], whereas rheological and mechanical testing characterise viscoelastic behaviour, tensile properties, and processability in hydrogels and composite biomaterials [20, 21, 29].

Collectively, these methods demonstrate a high capacity for polymer structure-function analysis across Jordanian research groups. However, they are rarely paired with elemental (section 5.1) or comprehensive organic contaminant screening (section 5.2). This creates a structural-chemical disconnect, where materials are well-characterised mechanically and morphologically, but not safety-validated at the trace contaminant level relevant to biomedical exposure. Table **2** summarises this explicitly.

5.4. Emerging Challenges

Biopolymer fragmentation generates micro- and nanoplastics with altered surface chemistry and contaminant content, producing degradation products such as oxidised metal complexes, hydrolysed crosslinker fragments, and metal-chelate complexes that were not present in the original formulation and thus lack reference standards for detection. Characterising these would require highly advanced analytical techniques (e.g., coupling non-target HRMS with single-particle ICP-MS, which is specific for nanoparticles, to simultaneously track particle counts, size distributions, and elemental states), however, such instrumentation is difficult to attain in all the local academic hubs where biopolymer research is undertaken, as well as that approaches are restricted by the absence of standardised reference materials and protocols.

6. HUMAN EXPOSURE PATHWAYS

Biomedical implants represent the longest and most continuous exposure scenario (e.g., Cu-doped HAP/PCL membranes [46] and metal oxide-coated PLA screws [42] that release ions continuously over

Table 2: Analytical Coverage of the Jordanian Biopolymer Studies Reviewed

Polymer System	Structural Characterisation	Organic E&L Screening	Elemental Screening
Alginate	Comprehensive	Unperformed	XRF (to validate crosslinking ion)
Chitosan			FESEM-EDX
Hyaluronic Acid			Unperformed
Carrageenan			
Cellulose		GPC (for molar mass data)	SEM-EDS
Starch/Cyclodextrins		Unperformed	Unperformed
PHA		IRMS (to investigate biopolymer origin) GPC (for molar mass data)	
PLA		Unperformed	
PCL			
Gum Arabic			
Zein			

two-to-three-year PCL degradation timelines). Standard *in vitro* release testing at neutral pH systematically underestimates ion release at the implant surface, where activated macrophages during the foreign-body response lower local pH to 4–5 and generate ROS, conditions that would accelerate metal liberation from crosslinked matrices beyond what neutral-pH dissolution studies predict. Cumulative ion burden over the years cannot be inferred from short-term release data.

Drug delivery systems transform exposure into a controlled kinetic process, but any inorganic impurities embedded in the polymer matrix are co-released by the same diffusion and erosion kinetics that govern the API. For carrageenan-based sustained-release tablets and Fe-crosslinked hydrogels, co-released species are not characterised in pharmacokinetic studies (section 2.4). The zein case is distinct (section 2.11), as the amino acid functional groups that make zein's drug release sensitive to ionic strength [52] are the same groups independently shown to bind Cr(VI) at pH 2.0 [54], therefore predicting that trace metals present in gastric fluid, or in the zein excipient itself, will alter release kinetics.

Cosmetics and personal care products introduce chronic, repeated dermal exposure, often on compromised skin barriers (i.e., the very condition for which HA anti-ageing products are promoted) [19]. Even low per-application doses of metal contaminants from Fe(III)-crosslinked HA formulations or trace metals in glycerophosphate excipients accumulate differently under daily use than under the single-application conditions of standard E&L testing (section 4.3). Chitosan's metal-chelating capacity when applied to the skin may actively redistribute trace metals from the skin surface, formulation, or environmental deposition [Algburi *et al*., 2025]. As for protein-containing biopolymers (e.g., Gum Arabic's arabinogalactan-protein fraction) [48], they present inherent allergenicity risks independent of metal contaminants.

Fragrance delivery, another repetitive form of exposure amongst the general public, adds inhalation as a distinct route. When cyclodextrin (the most commonly used biopolymer for this route) microcapsules rupture on skin or fabric, they co-release volatile organic compounds (VOCs), along with any degradation products or trace contaminants associated with the CD matrix. Inhalation also bypasses the dermal and gastrointestinal barriers entirely, underscoring the importance of aerosolised particle size and co-contaminant profiles [35].

The implication across the reviewed routes is the same: the main question influencing exposure is not structural (how does the polymer perform?) but elemental (what does it co-release, and through which barrier, at what rate?). Because these four exposure routes differ by an order of magnitude in duration, barrier permeability, and clearance mechanism, a single E&L protocol cannot adequately characterise risk across all of them; thus, route-specific testing conditions are required.

7. LIFE CYCLE ASSESSMENT AND CIRCULAR ECONOMY

7.1. Methodological Gaps in Bioplastic LCA

Elsewhere in the Levant, upon reviewing over 50 bioplastic LCA studies, it was found that toxicological fate is determined primarily by methodological choices, such as biogenic carbon accounting conventions, land-use change treatment, allocation rules, and regional inventory selection, rather than by renewable origin. For example, growing crops for bioplastics instead of food indirectly forces agricultural expansion elsewhere, which releases stored carbon, while fertiliser and irrigation use increase acidification and eutrophication impacts even if CO_2 emissions decrease. The review explicitly identifies MENA-specific life-cycle inventory data as a current gap requiring a regionalised water scarcity assessment (the AWARE, or Available Water Remaining, method), as European default values fail to capture the environmental reality [89].

A Mediterranean feedstock analogue (Greek agricultural residues including olive by-products, citrus peels, and grape pomace evaluated for cellulose-, lignin-, and pectin-based biomaterials) confirms that the technical potential for valorising Jordan's equivalent feedstocks is regionally validated. However, the regional inventory, coordinated policy support, and contamination monitoring frameworks are identified as necessary for sustainable implementation [90], but are absent from the Jordanian context.

As for the downstream use phase, it is commonly omitted, and end-of-life is modelled on generic rather than material-specific data. This is of particular consequence for biomedical polymers, where sections 4 and 6 of this review identify the use phase as the principal human exposure stage, and it is precisely this stage that current LCA data typically omit [91].

7.2. Manufacturing to End-of-Life and Verification Necessity

The University of Jordan reviewed green polymer nanocomposites, confirming that nanofiller

incorporation substantially improves mechanical performance, whilst acknowledging nanomaterial safety as an unresolved concern that would require further investigation [92]. This relates to how various literature promotes the advantages of green synthesis based solely on renewable feedstocks, while omitting the environmental impacts of residual catalysts, purification solvents, and leached metal nanoparticles (section 3), despite the rising industrial applications and adoption in packaging, medical devices and formulations, agriculture, etc., all of which scale up the impact of contamination.

At the end-of-life stage, researchers confirm that biodegradable vs. conventional plastics are typically indistinguishable without spectroscopy, making separation at Jordan's current Al-Karak facility impossible [93]. When biopolymers enter the recycling streams for conventional, synthetic plastics, they degrade the quality of the recycled output, as demonstrated by PLA and PHB contamination of PET recycling. It is also noted that biodegradation under anaerobic digestion often differs from that under aerobic conditions, which would require implementing end-of-life pathways specific to a given material rather than a blanket "biodegradable" labelling. Such pathways include advances in chemical and enzymatic recycling strategies to recover high-value polymers, such as enzymatic hydrolysis, glycolysis, or methanolysis under low temperatures, or thermal pyrolysis to retrieve virgin-grade monomers (e.g., lactic acid); however, their implementation remains limited in many regions internationally, including Jordan [94, 95].

A missing link within waste management strategies is connecting the design of a material with laws governing its collection, sorting, and treatment, even in the EU [96], but said gap is even more acute in Jordan, where, even though such "greener" alternatives are promoted [58], regulations in the sector are still limited to either chemical safety of finished pharma- and cosmeceuticals (e.g. JS ISO 17276) or to ensuring biodegradability of bioplastic as packaging materials (JS EN 13432), rather than chemical safety of them as excipients [97].

7.3. What a Credible and Holistic Jordanian Biopolymer LCA Requires

Four departures from current default LCA practice would be needed: (1) MENA-specific LCI data replacing European defaults; (2) explicit use-phase modelling incorporating metal ion release and additive migration rather than omitting this stage; (3) end-of-life scenarios reflecting Jordan's actual >90% landfill reality rather than idealised composting; and (4) full-cycle metal mass balance tracking heavy metals from contaminated feedstock through manufacturing, use, and end-of-life redistribution. For example, applying an AWARE-based regional water-scarcity characterisation factor to Jordan Valley cereal cultivation, rather than the European default, would be expected to substantially increase the water-scarcity footprint attributed to Jordanian starch-based feedstocks relative to current estimates, though the precise magnitude requires a dedicated study. The primary limitations are institutional and regulatory rather than technological, as sorting mechanisms, even those dependent on artificial intelligence, exist internationally and can be imported or implemented locally, but there is a lack of regional policy.

8. DISCUSSION

There are findings from independently authored sections that are consistent throughout this review, where their convergence is itself evidential. As, when compared with the broader sustainable polymer literature, the Jordanian studies reviewed demonstrate strong material development and structural characterisation, but they consistently lack comprehensive contaminant screening, long-term exposure assessments, and region-specific life-cycle data.

First, biodegradability and chemical safety are empirically dissociated, not synonymous. This is established at the toxicological level [3], where origin does not predict chemical complexity or cytotoxicity, and independently at the LCA methodology level [90], where origin does not predict environmental performance. Two different scientific literatures arriving at structurally identical conclusions are strong grounds for treating the dissociation as a robust finding rather than a perspective.

Second, Jordan possesses a unique contamination pathway that its biopolymer literature has not yet considered. Geological studies establishing mineral enrichment (section 3.2) sit alongside a polymer science literature that routinely characterises influenceable feedstocks (e.g., starch, cellulose, PHA, gum Arabic, and chitosan) (section 2), using mainly structural methods ncapable of resolving trace elemental contamination at levels of regulatory concern (section 5.3). The mismatch is between what is

measured (mechanical, thermal, and release properties) and what is needed to verify safety (trace elemental and organic-chemical contaminant profiles under exposure-route-relevant conditions).

Based on the current evidence, the likelihood of contamination can be tiered, with starch, zein, and olive-derived cellulose carrying the most direct contamination risk through feedstock contact with phosphate-fertilised soils. Gum Arabic and Dead-Sea-fermented PHA carry plausible but unmeasured pathways via protein-metal coordination chemistry and halophilic metal accumulation. As for intentionally metal-functionalised systems (e.g., Cu-alginate, Fe HA/carrageenan), they present deliberate dose-dependent exposure distinct from incidental contamination, though it is not unlikely for both to coexist in Jordanian-sourced materials.

Closing the various recurring gaps requires a coordinated initiative, including: (1) ICP-MS screening of the highest-plausibility feedstocks (starch, zein, olive cellulose) using external laboratory collaboration where institution-based access is limited; (2) Expanding extractables and leachables protocols to characterize metal migration under realistic local exposure conditions of high salinity; (3) building LCA on regional inventory data with explicit use-phase dynamics and actual domestic waste infrastructure; and (4) regulatory engagement with JFDA and JISM to establish contaminant screening as a strict requirement for pharmaceutical-grade biopolymers.

9. CONCLUSION

Transitioning away from petroleum-derived plastics is a necessary environmental objective, but true sustainability requires verifying that alternative materials are chemically safe throughout their entire life cycle. Investigating whether geogenic contaminants accompany Jordan's downstream bioeconomy products is an essential task for future research, as this review argues, rather than promoting reassurance or alarm.

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AUTHOR'S CONTRIBUTIONS

This work was carried out in collaboration among all authors. Authors LAS and IIA contributed to data collections and wrote the original draft manuscript, which was edited and improved by authors LNA and AMA. All authors have read and agreed to the published version of the manuscript.

COMPETING INTERESTS

The authors have declared that no competing interests exist.

REFERENCES

[1] Repinc SK, Stres B, Karlovits M, Karlovits I, Jerič P, Panák O, *et al*. Understanding bio-based polymers: A study of origins, properties, biodegradation and their impact on health and the environment. FEBS Open Bio 2026; 16: 635-52. https://doi.org/10.1002/2211-5463.70183

[2] Pamakštys K, Sholokhova A, Gurauskienė I, Varžinskas V. Environmental assessment strategies for biodegradable polymer composites: a review of life cycle perspectives on agro-waste reinforced materials. Polymers 2026; 18: 700. https://doi.org/10.3390/polym18060700

[3] Zimmermann L, Dombrowski A, Völker C, Wagner M. Are bioplastics and plant-based materials safer than conventional plastics? *In vitro* toxicity and chemical composition. Environment International 2020; 145: 106066. https://doi.org/10.1016/j.envint.2020.106066

[4] Gharaibeh MA, Marschner B, Moos N, Monokrousos N. Spatial distribution and management of trace elements in arid agricultural systems: a geostatistical assessment of the jordan valley. Land 2025; 14: 1325. https://doi.org/10.3390/land14071325

[5] Batarseh M, El-Hasan T. Toxic element levels in the phosphate deposits of central jordan. Soil and Sediment Contamination: An International Journal 2009; 18: 205-15. https://doi.org/10.1080/15320380802660214

[6] Circular solutions to tackle plastic pollution in Jordan's food and beverage packaging sector. United Nations Development Program 2025. https://www.undp.org/jordan/press-releases/circular-solutions-tackle-plastic-pollution-jordans-foo d-and-beverage-packaging-sector

[7] Umoren SA, Solomon MM, Saji VS. Alginate and its derivatives. Polymeric Materials in Corrosion Inhibition, Elsevier 2022; pp. 271-86. https://doi.org/10.1016/B978-0-12-823854-7.00014-X

[8] Jaradat A, Alazzo A, Bayan MF, Obeidat W. A green, solvent- and cation-free approach for preparing 5-fluorouracil-loaded alginate nanoparticles using microfluidic technology. Pharmaceutics 2025; 17: 438. https://doi.org/10.3390/pharmaceutics17040438

[9] Al-Najjar MAA, Athamneh T, AbuTayeh R, Basheti I, Leopold C, Gurikov P, *et al*. Evaluation of the orally administered calcium alginate aerogel on the changes of gut microbiota and hepatic and renal function of Wistar rats. PLoS ONE 2021; 16: e0247633. https://doi.org/10.1371/journal.pone.0247633

[10] Athamneh T, Al-Najjar MAA, Garafat R, Abuawad AM, Alshweiat A, Barakat M, *et al*. Preparation and characterization of copper-crosslinked alginate-hyaluronic acid aerogels as potential wound dressing materials with enhanced antibacterial properties. Polymers 2025; 17: 2406. https://doi.org/10.3390/polym17172406

[11] Athamneh T, Abuawad A, Odat T, Alshweiat A, Obaidat R, Bani Yaseen F, *et al*. Investigation of the antibacterial activity of zno-loaded alginate/hyaluronic acid aerogels for wound dressing applications. Polymers 2025; 17: 506. https://doi.org/10.3390/polym17040506

[12] Desaulniers D, Zhou G, Stalker A, Cummings-Lorbetskie C. Effects of copper or zinc organometallics on cytotoxicity, dna

damage and epigenetic changes in the hc-04 human liver cell line. IJMS 2023; 24: 15580. https://doi.org/10.3390/ijms242115580

[13] Al-Sou'oda K, Abu-Falaha R, Al-Remawi M. Surface activity of some low molecular weight chitosan derivatives. JJC 2013; 8: 1-17. https://doi.org/10.12816/0001512

[14] Matalqah SM, Aiedeh K, Mhaidat NM, Alzoubi KH, AL-Husein BA. Preparation of modified chitosan-based nanoparticles for efficient delivery of doxorubicin and/or cisplatin to breast cancer cells. CCDT 2022; 22: 133-41. https://doi.org/10.2174/1568009622666220126100532

[15] Youssef K, Hashim AF. Inhibitory effect of clay/chitosan nanocomposite against penicillium digitatum on citrus and its possible mode of action. JJBS 2020; 13: 349-55. https://jjbs.hu.edu.jo/files/vol13/n3/Paper%20Number%2013.pdf

[16] Abdulhameed AS, Alsayer IA, Al Omari RH, Abualhaija M, Algburi S. Sustainable polymeric adsorbent of chitosan and acid-modified agricultural waste lettuce (Lactuca sativa L.) leaf for efficient methylene blue dye removal: sustainable water treatment and biomass valorization. Environ Dev Sustain 2025. https://doi.org/10.1007/s10668-025-06188-2

[17] Al Tawaha AR, Turk M, Al Tawaha AR, Aludatt M, Wedyan M, Al-ramamneh EA-D, *et al*. Using chitosan to improve growth of maize cultivars under salinity conditions. BJAS 2018; 24: 437-42. https://www.agrojournal.org/24/03-13.pdf

[18] Zhao X. Bioactive materials in plastic surgery and body reconstruction. Bioactive Materials in Medicine, Elsevier 2011; pp. 220-46. https://doi.org/10.1533/9780857092939.2.220

[19] Al-Halaseh LK, Tarawneh SK, Al-Jawabri NA, Al-Qdah WK, Abu-Hajleh MN, Al-Samydai AM, *et al*. A review of the cosmetic use and potentially therapeutic importance of hyaluronic acid. J App Pharm Sci 2022: 34-41. https://doi.org/10.7324/JAPS.2022.120703

[20] Mashaqbeh H, Hamed R, Obaidat R, Hmedat A, Aburayya R, Hijazi S, *et al*. Hyaluronic acid and K-carrageenan metal ionic cross-linked polymers: a promising injectable hydrogels for prolonged chemotherapeutic drug delivery. Journal of Biomaterials Science, Polymer Edition 2026; 37: 251-80. https://doi.org/10.1080/09205063.2025.2524059

[21] Mashaqbeh H, Hamed R, Alzoubi H, Obaidat R, Alnaeif M, Rezigue M, *et al*. Hyaluronic acid/chitosan/glycerophosphate-based in situ-forming hydrogel for accelerated wound healing. Gels 2025; 11: 835. https://doi.org/10.3390/gels11100835

[22] Jabeen F, Zil-e-Aimen, Ahmad R, Mir S, Awwad NS, Ibrahium HA. Carrageenan: structure, properties and applications with special emphasis on food science. RSC Adv 2025; 15: 22035-62. https://doi.org/10.1039/D5RA03296B

[23] Obaidat RM, Alnaief M, Mashaqbeh H. Investigation of carrageenan aerogel microparticles as a potential drug carrier. AAPS PharmSciTech 2018; 19: 2226-36. https://doi.org/10.1208/s12249-018-1021-4

[24] Alnaief M, Obaidat R, Mashaqbeh H. Loading and evaluation of meloxicam and atorvastatin in carrageenan microspherical aerogels particles. J App Pharm Sci 2019; 9: 83-8. https://doi.org/10.7324/JAPS.2019.90112

[25] Abdullah S, Thiab S, A. Al-Masud A, Marzoog Al-Sharafa M, Ardakani A. Carrageenan matrix for sustained levofloxacin delivery: formulation strategies and dual evaluation approaches. J Pharm Innov 2025; 20: 142. https://doi.org/10.1007/s12247-025-10043-2

[26] Mokhtari H, Tavakoli S, Safarpour F, Kharaziha M, Bakhsheshi-Rad HR, Ramakrishna S, *et al*. Recent advances in chemically-modified and hybrid carrageenan-based platforms for drug delivery, wound healing, and tissue engineering. Polymers 2021; 13: 1744. https://doi.org/10.3390/polym13111744

[27] Nasution H, Harahap H, Dalimunthe NF, Ginting MHS, Jaafar M, Tan OOH, *et al*. Hydrogel and effects of crosslinking agent on cellulose-based hydrogels: a review. Gels 2022; 8: 568. https://doi.org/10.3390/gels8090568

[28] Hamed OA, Jodeh S, Al-Hajj N, Hamed EM, Abo-Obeid A, Fouad Y. Cellulose acetate from biomass waste of olive industry. J Wood Sci 2015; 61: 45-52. https://doi.org/10.1007/s10086-014-1442-y

[29] AL-Oqla FM, Hayajneh MT, Fares O. Investigating the mechanical thermal and polymer interfacial characteristics of Jordanian lignocellulosic fibers to demonstrate their capabilities for sustainable green materials. Journal of Cleaner Production 2019; 241: 118256. https://doi.org/10.1016/j.jclepro.2019.118256

[30] Harb AM, Lahham JN. Cellulose content in selected plant species along the dead sea coast and the southern desert of jordan. JJBS 2020; 13: 343-7. https://jjbs.hu.edu.jo/files/vol13/n3/Paper%20Number%2012.pdf

[31] Kankanamge SU, Jayasuriya WJABN, Herath HMDR, Pathirana RN. Alternative natural sources for commercialised starches as pharmaceutical excipients; Physicochemical properties and applications. Indian J Nat Prod Resour 2025; 16. https://doi.org/10.56042/ijnpr.v16i1.11272

[32] Ibrahim KA, Naz MY, Shukrullah S, Sulaiman SA, Ghaffar A, AbdEl-Salam NM. Nitrogen pollution impact and remediation through low cost starch based biodegradable polymers. Sci Rep 2020; 10: 5927. https://doi.org/10.1038/s41598-020-62793-3

[33] Sezer M, Dıbek E, Çöl B. Importance of some metalloids in biological life. MJST 2018; 4: 236-41. https://doi.org/10.22531/muglajsci.466007

[34] Yong H, Liu J. Recent advances on the preparation conditions, structural characteristics, physicochemical properties, functional properties and potential applications of dialdehyde starch: A review. International Journal of Biological Macromolecules 2024; 259: 129261. https://doi.org/10.1016/j.ijbiomac.2024.129261

[35] Perinelli DR, Palmieri GF, Cespi M, Bonacucina G. Encapsulation of flavours and fragrances into polymeric capsules and cyclodextrins inclusion complexes: an update. Molecules 2020; 25: 5878. https://doi.org/10.3390/molecules25245878

[36] Mashaqbeh H, Obaidat R, Al-Shar'i NA, El-Elimat T, Alnabulsi S. Weak complexation of 5-fluorouracil with β-cyclodextrin, carbonate, and dianhydride crosslinked β-cyclodextrin: *in vitro* and in silico studies. RPS 2022; 17: 334-49. https://doi.org/10.4103/1735-5362.350235

[37] Gomes Gradíssimo D, Pereira Xavier L, Valadares Santos A. Cyanobacterial polyhydroxyalkanoates: a sustainable alternative in circular economy. Molecules 2020; 25: 4331. https://doi.org/10.3390/molecules25184331

[38] Alsafadi D, Ibrahim MI, Alamry KA, Hussein MA, Mansour A. Utilizing the crop waste of date palm fruit to biosynthesize polyhydroxyalkanoate bioplastics with favorable properties. Science of The Total Environment 2020; 737: 139716. https://doi.org/10.1016/j.scitotenv.2020.139716

[39] Alsafadi D, Aljariri Alhesan JS, Mansoura A, Oqdeha S. Production of polyhydroxyalkanoate from sesame seed wastewater by sequencing batch reactor cultivation process of Haloferax mediterranei. AJC 2023; 16: 104584. https://doi.org/10.1016/j.arabjc.2023.104584

[40] Al-Daghistani HI, Zein S, Abbas MA. Microbial communities in the Dead Sea and their potential biotechnological applications. Communicative & Integrative Biology 2024; 17: 2369782. https://doi.org/10.1080/19420889.2024.2369782

[41] Kost B, Basko M, Bednarek M, Socka M, Kopka B, Łapienis G, *et al*. The influence of the functional end groups on the properties of polylactide-based materials. Progress in Polymer Science 2022; 130: 101556. https://doi.org/10.1016/j.progpolymsci.2022.101556

[42] Altarawneh Y, Hammouri Y, Shehab M, Abdelall E. Synergistic enhancements in additive manufactured polylactic acid orthopedic cortical screws: nano coating strategies and comparative performance analysis. Sustainable Approaches to Environmental Design, Materials Science, and Engineering Technologies, Vol. 1, Cham: Springer Nature Switzerland 2025; pp. 265-71. https://doi.org/10.1007/978-3-031-76025-9_26

[43] Kirkland D, Aardema MJ, Battersby RV, Beevers C, Burnett K, Burzlaff A, *et al*. A weight of evidence review of the genotoxicity of titanium dioxide (Tio2). Regulatory Toxicology and Pharmacology 2022; 136: 105263. https://doi.org/10.1016/j.yrtph.2022.105263

[44] Krause BC, Kriegel FL, Rosenkranz D, Dreiack N, Tentschert J, Jungnickel H, *et al*. Aluminum and aluminum oxide nanomaterials uptake after oral exposure - a comparative study. Sci Rep 2020; 10: 2698. https://doi.org/10.1038/s41598-020-59710-z

[45] Deshpande MV, Girase A, King MW. Degradation of poly(E-caprolactone) resorbable multifilament yarn under physiological conditions. Polymers 2023; 15: 3819. https://doi.org/10.3390/polym15183819

[46] Alrafai HA, Ali Al-Ahmed Z, Ahmed MK, Afifi M, Shoueir KR, Abu-Rayyan A. The degradation of methylene blue dye using copper-doped hydroxyapatite encapsulated into polycaprolactone nanofibrous membranes. New J Chem 2021; 45: 16143-54. https://doi.org/10.1039/D1NJ01623G

[47] Mohamed SA, Elsherbini AM, Alrefaey HR, Adelrahman K, Moustafa A, Egodawaththa NM, *et al*. Gum arabic: a commodity with versatile formulations and applications. Nanomaterials 2025; 15: 290. https://doi.org/10.3390/nano15040290

[48] Awad MH, Hassan EA, Osmon ME, Alassaf S, Phillips GO. Emulsification properties and molecular weight distribution of combretum glutinosum gum. JJC 2013; 8: 139-51. https://doi.org/10.12816/0001524

[49] Roque ACA, Wilson OC. Adsorption of gum Arabic on bioceramic nanoparticles. Materials Science and Engineering: C 2008; 28: 443-7. https://doi.org/10.1016/j.msec.2007.04.009

[50] Tauseef M, Azam F, Iqbal Y, Ahmad S, Ahmad F, Masood R, *et al*. Development and evaluation of silver-infused Biopolymer coated cotton wound dressings as possible wound healing material. Heliyon 2024; 10: e38407. https://doi.org/10.1016/j.heliyon.2024.e38407

[51] Lima IBC, Moreno LCGAI, Peres AV, Santana ACG, Carvalho A, Chaves MH, *et al*. Nanoparticles obtained from zein for encapsulation of mesalazine. Pharmaceutics 2022; 14: 2830. https://doi.org/10.3390/pharmaceutics14122830

[52] Berardi A, Bisharat L, AlKhatib HS, Cespi M. Zein as a pharmaceutical excipient in oral solid dosage forms: state of the art and future perspectives. AAPS PharmSciTech 2018; 19: 2009-22. https://doi.org/10.1208/s12249-018-1035-y

[53] Berardi A, Abdel Rahim S, Bisharat L, Cespi M. Swelling of zein matrix tablets benchmarked against hpmc and ethylcellulose: challenging the matrix performance by the addition of co-excipients. Pharmaceutics 2019; 11: 513. https://doi.org/10.3390/pharmaceutics11100513

[54] Ansari S, Ahmed N, Mahar RB, Khatri Z, Khatri M. Fabrication and characterization of electrospun zein/nylon-6 (Zn6) nanofiber membrane for hexavalent chromium removal. Environ Sci Pollut Res 2022; 29: 653-62. https://doi.org/10.1007/s11356-021-15729-x

[55] Al Shomali M, Sharif AA, Al Omari O. Developing spatial typology for urban agriculture initiatives to achieve food security in Jordan. GTG 2022; 45: 1726-34. https://doi.org/10.30892/gtg.454spl22-993

[56] Shammout MW, Qtaishat T, Rawabdeh H, Shatanawi M. Improving water use efficiency under deficit irrigation in the jordan valley. Sustainability 2018; 10: 4317. https://doi.org/10.3390/su10114317

[57] Al-Sababhah N. Land suitability and capability analysis for sustainable allocation of agricultural crops and natural plants, northwest jordan. J Geovis Spat Anal 2024; 8: 1. https://doi.org/10.1007/s41651-023-00150-4

[58] Shalamai O. Green growth in jordan: leveraging waste management for sustainability, poverty reduction, and social development. GJNR 2024; 7: 271-86. https://doi.org/10.33002/nr2581.6853.070315

[59] Yang H, Zhang F, Zhou J, Zhu J, Cui D, Zhang X, *et al*. The hazards of metal exposure mediated by crops to human health from perspective of environmental health and control strategies. iScience 2026; 29: 116147. https://doi.org/10.1016/j.isci.2026.116147

[60] Awad A. Analyzing the situation of municipal solid waste in Amman City using small cell areas. CSCEE 2025; 11: 101009. https://doi.org/10.1016/j.cscee.2024.101009

[61] Al-Athamin EA, Hemidat S, Al-Hamaiedeh H, Aljbour SH, El-Hasan T, Nassour A. A techno-economic analysis of sustainable material recovery facilities: the case of al-karak solid waste sorting plant, jordan. Sustainability 2021; 13: 13043. https://doi.org/10.3390/su132313043

[62] Abu-Qdais H, Al-Omoush S, Jalalipour H, Nassour A. Towards a circular economy in Jordan: selecting organic waste treatment options using a multi-criteria decision-making approach. Sustainability 2025; 17: 2146. https://doi.org/10.3390/su17052146

[63] Arabiyat O, Al-Bakri J, Kölsch F, Al-Omari S, Aladwan H. Enhancing sustainable solid waste management through separate source collection. Global J Environ Sci Manage 2024; 10: 1-14. https://doi.org/10.22035/gjesm.2024.03

[64] Shbool MA, Altarawneh Y, Bani Hamad R, Alqa'aydeh R, Al-Tahat MD, Abedeljawad T, *et al*. Predictive modeling of chemical waste generation in healthcare facilities: enhancing waste management strategies. AJS 2025; 12: 9-32. https://doi.org/10.30958/ajs.12-1-1

[65] Hendi A, Al-Hrinat J, Al-Ansi AM, Hazaimeh M. Strategies for optimizing medical waste management and treatment technologies in Jordanian hospitals. OCS 2024; 3: 35-49. https://doi.org/10.56578/ocs030103

[66] Cai P-T, Chen T, Chen B, Wang Y-C, Ma Z-Y, Yan J-H. The impact of pollutant emissions from co-incineration of industrial waste in municipal solid waste incinerators. Fuel 2023; 352: 129027. https://doi.org/10.1016/j.fuel.2023.129027

[67] Kricheldorf HansR, Weidner SM. About the Toxicity of Polymerization Catalysts and Polymer Additives Based on Tin(II) Salts and Tin(IV) Compounds. ACS Chem Health Saf 2025; 32: 677-89. https://doi.org/10.1021/acs.chas.5c00105

[68] Kim TH, Kim HS, Lee S-H. Sustainable Polyurethane Systems: Integrating Green Synthesis and Closed-Loop Recovery. Polymers 2026; 18: 246. https://doi.org/10.3390/polym18020246

[69] James CC, De Bruin B, Reek JNH. Transition Metal Catalysis in Living Cells: Progress, Challenges, and Novel Supramolecular Solutions. Angew Chem Int Ed 2023; 62: e202306645. https://doi.org/10.1002/anie.202306645

[70] Compart J, Singh A, Fettke J, Apriyanto A. Customizing Starch Properties: A Review of Starch Modifications and Their Applications. Polymers 2023; 15: 3491. https://doi.org/10.3390/polym15163491

[71] Dagnino EP, Ehman N, Area MC. Recent Advances in Cellulose Nanocrystal Production from Green Methods. Processes 2025; 13: 790. https://doi.org/10.3390/pr13030790

[72] Hakeem IG, Halder P, Marzbali MH, Patel S, Rathnayake N, Surapaneni A, *et al*. Mild sulphuric acid pre-treatment for metals removal from biosolids and the fate of metals in the treated biosolids derived biochar. JECE 2022; 10: 107378. https://doi.org/10.1016/j.jece.2022.107378

[73] Qiu Y, Zhao Z, Hu F, Liu M, Shi X. One-Step Synergistic SDS-H2O2 Process for High-Purity Chitin Extraction from Fly Larvae. Polymers 2025; 17: 994. https://doi.org/10.3390/polym17070994

[74] Murat P, Harohalli Puttaswamy S, Ferret P-J, Coslédan S, Simon V. Identification of Potential Extractables and Leachables in Cosmetic Plastic Packaging by Microchambers-Thermal Extraction and Pyrolysis-Gas Chromatography-Mass Spectrometry. Molecules 2020; 25: 2115. https://doi.org/10.3390/molecules25092115

[75] Aliotta L, Vannozzi A, Panariello L, Gigante V, Coltelli M-B, Lazzeri A. Sustainable Micro and Nano Additives for Controlling the Migration of a Biobased Plasticizer from PLA-Based Flexible Films. Polymers 2020; 12: 1366. https://doi.org/10.3390/polym12061366

[76] Dintcheva NT, Infurna G, Baiamonte M, D'Anna F. Natural Compounds as Sustainable Additives for Biopolymers. Polymers 2020; 12: 732. https://doi.org/10.3390/polym12040732

[77] Chan CM, Yim S, Lant P, Pratt S, Laycock B. The impact of functional additives on biodegradable plastic biodegradation in natural terrestrial and composting environments. Critical Reviews in Environmental Science and Technology 2025; 55: 708-31. https://doi.org/10.1080/10643389.2024.2443284

[78] Alsaad AM, Al-Bataineh QM, Ahmad AA, Jum'h I, Alaqtash N, Bani-Salameh AA. Optical properties of transparent PMMA-PS/ZnO NPs polymeric nanocomposite films: UV-Shielding applications. Mater Res Express 2020; 6: 126446. https://doi.org/10.1088/2053-1591/ab68a0

[79] Yang X, Xu H, Li W, Chang X, Jiang X, Liu X, *et al*. Effects of Nanomaterials on Crops. CIMB 2025; 47: 1024. https://doi.org/10.3390/cimb47121024

[80] Sadeghifar H, Ragauskas A. Lignin as a UV Light Blocker—A Review. Polymers 2020; 12: 1134. https://doi.org/10.3390/polym12051134

[81] Sandouqa A, Al-Hamamre Z, Asfar J. Structural characteristics of lignin extracted from Jordanian olive cake using different fractionation conditions. Energy Sources, Part A: Recovery, Utilization, and Environmental Effects 2023; 45: 3831-42. https://doi.org/10.1080/15567036.2019.1668877

[82] Yao X, Yang X, Lu Y, Qiu Y, Zeng Q. Review of the Synthesis and Degradation Mechanisms of Some Biodegradable Polymers in Natural Environments. Polymers 2024; 17: 66. https://doi.org/10.3390/polym17010066

[83] Edo GI, Ndudi W, Ali AliBM, Yousif E, Jikah AN, Isoje EF, *et al*. Biopolymers: An inclusive review. Hybrid Advances 2025; 9: 100418. https://doi.org/10.1016/j.hybadv.2025.100418

[84] Carboué Q, Fadlallah S, Lopez M, Allais F. Progress in Degradation Behavior of Most Common Types of Functionalized Polymers: A Review. Macromol Rapid Commun 2022; 43: 2200254. https://doi.org/10.1002/marc.202200254

[85] Malafeev K. The Cytotoxicity of Biodegradable Microplastics and Nanoplastics: Current Status and Research Prospects. Microplastics 2025; 4: 58. https://doi.org/10.3390/microplastics4030058

[86] Kuzmič S, Zlobec T, Dolenc M, Roškar R, Lušin T. Extractables and Leachables in Pharmaceutical Products: Potential Adverse Effects and Toxicological Risk Assessment. Toxics 2026; 14: 92. https://doi.org/10.3390/toxics14010092

[87] Bartnick R, Rodionov A, Oster SDJ, Löder MGJ, Lehndorff E. Plastic Quantification and Polyethylene Overestimation in Agricultural Soil Using Large-Volume Pyrolysis and TD-GC-MS/MS. Environ Sci Technol 2024; 58: 13047-55. https://doi.org/10.1021/acs.est.3c10101

[88] Rizzarelli P, Leanza M, Rapisarda M. Investigations into the characterization, degradation, and applications of biodegradable polymers by mass spectrometry. Mass Spectrometry Reviews 2025; 44: 947-88. https://doi.org/10.1002/mas.21869

[89] El Bachawati M, Belarbi YE, El Zakhem H, Belarbi R. Life Cycle Assessment of Sustainable Materials: A Comprehensive Analysis of Methodological Asymmetries and Environmental Trade-Offs. Buildings 2026; 16: 1385. https://doi.org/10.3390/buildings16071385

[90] Kiskira K, Plakantonaki S, Nikolopoulos D, Sfyroera E, Gerolimos N, Priniotakis G, *et al*. Valorization of Fruit and Nut Agricultural Residues for Sustainable Biomaterials and Biotextiles: A Qualitative Review with Strategic Insights for Greece. Environments 2026; 13: 221. https://doi.org/10.3390/environments13040221

[91] Molina-Besch K. Use phase and end-of-life modeling of biobased biodegradable plastics in life cycle assessment: a review. Clean Techn Environ Policy 2022; 24: 3253-72. https://doi.org/10.1007/s10098-022-02373-3

[92] Abu-Zurayk R, Khalaf A, Alnairat N, Waleed H, Bozeya A, Abu-Dalo D, *et al*. Green polymer nanocomposites: bridging material innovation with sustainable industrial practices. Front Mater 2025; 12: 1701086. https://doi.org/10.3389/fmats.2025.1701086

[93] Taneepanichskul N, Purkiss D, Miodownik M. A Review of Sorting and Separating Technologies Suitable for Compostable and Biodegradable Plastic Packaging. Front Sustain 2022; 3: 901885. https://doi.org/10.3389/frsus.2022.901885

[94] Siddiqui MN, Redhwi HH, Al-Arfaj AA, Achilias DS. Chemical Recycling of PET in the Presence of the Bio-Based Polymers, PLA, PHB and PEF: A Review. Sustainability 2021; 13: 10528. https://doi.org/10.3390/su131910528

[95] Zaborowska M, Bernat K. The development of recycling methods for bio-based materials - A challenge in the implementation of a circular economy: A review. Waste Manag Res 2023; 41: 68-80. https://doi.org/10.1177/0734242X221105432

[96] Mhaddolkar N, Astrup TF, Tischberger-Aldrian A, Pomberger R, Vollprecht D. Challenges and opportunities in managing biodegradable plastic waste: A review. Waste Manag Res 2025; 43: 911-34. https://doi.org/10.1177/0734242X241279902

[97] Standards Search. Jordan Standards and Metrology Organization 2026. https://eservice.jsmo.gov.jo/en/Standards

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https://doi.org/10.6000/1929-5995.2026.15.08