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Functional Textiles and Natural Colourants Derived from Agro-Food Waste: A Comprehensive Review of Their Application in Food Quality Monitoring, Active Packaging, and the Circular Bioeconomy

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Abstract

The global food system faces a dual sustainability crisis: huge quantities of agro-food waste are generated annually, while food safety monitoring and preservation remain heavily dependent on resource-intensive, non-renewable materials and methods. This review explores the emerging interdisciplinary field that connects textile engineering, natural colourant chemistry, and food science. We provide a comprehensive and critical synthesis of more than 120 peer-reviewed studies published between 2020 and 2026. The paper is organised around three interconnected pillars. First, we examine the valorisation of agro-food residues – including mango seed kernel, Aronia pomace, orchid blooms, grape pomace, pomegranate peels, and Stevia leaves – as sources of natural colourants (anthocyanins, carotenoids, flavonoids, tannins) and bioactive finishing agents. Quantitative data are presented on extraction efficiencies (ultrasound-assisted vs. conventional), dyeing performance on various textile substrates (cotton, wool, silk, viscose, bacterial cellulose), and functional properties (antioxidant activity measured by DPPH and ABTS assays; antibacterial efficacy against *Escherichia coli* and *Staphylococcus aureus*; colour fastness to washing, light, and rubbing). The best-performing systems achieve DPPH scavenging >98%, ABTS >99%, and bacterial reduction >99%, with colour fastness ratings of 4–5 on the ISO scale. Second, we review textile-based sensor platforms developed for real-time, on-site food quality monitoring. These include: (i) cotton fabrics functionalised with molecularly imprinted polymers (MIPs) and nitrogen-doped carbon dots (N-CDs) for fluorescence detection of carbamate pesticides (detection limit 3.38 μg/L for carbofuran); (ii) covalent organic framework (COF)-modified textile sensors that exhibit solid-state chromism for time-temperature indication (−22 °C to 55 °C) and nanozyme activity for mycotoxin detection at sub-ppb levels; (iii) electrospun nanofibre mats incorporating pH-sensitive dyes for visual spoilage monitoring; and (iv) bacterial cellulose (BC) with in-situ biosynthesis of colourants for intelligent packaging. We compare analytical performance, reusability, and scalability. Third, we evaluate the application of these functional textiles in intelligent and active food packaging. Case studies show that COF-composite films extend the shelf life of beef and kumquat by fourfold, and coloured BC trays reduce microbial contamination without synthetic preservatives. A dedicated section critically discusses safety concerns related to heavy metal contamination of plant-derived materials, drawing on extensive Iranian studies (Alinia-Ahandani et al., 2020–2026) that have documented elevated lead, cadmium, and other toxic elements in medicinal plants and food products. We propose a quality control framework for plant-based colourants intended for food-contact applications. The review concludes with a research agenda that includes standardisation of test methods, life-cycle assessment, hybrid nanoparticle–plant extract systems, field validation, and regulatory harmonisation.

Keywords: *Functional textiles; natural colourants; agro-food waste valorisation; antibacterial and antioxidant finishing; textile-based sensors; molecularly imprinted polymers; covalent organic frameworks; bacterial cellulose; intelligent packaging; heavy metal contamination; circular bioeconomy; food quality monitoring*

Introduction

The Sustainability Imperative in Textiles and Food

The textile and food industries are two of the largest and most resource-intensive sectors of the global economy, and each faces its own distinct environmental crisis. The textile industry consumes approximately 79 billion cubic metres of water annually, discharges an estimated 200,000 tonnes of synthetic dyes into water bodies each year, and is responsible for 10% of global carbon emissions [1,2]. Many synthetic azo dyes are non-biodegradable, persist in the environment, and have been linked to allergic reactions, skin irritation, and potential carcinogenicity [3]. Conventional dyeing processes also rely on metal mordants such as chromium, copper, tin, and zinc, which accumulate in aquatic ecosystems and enter the food chain [4].

Simultaneously, the food industry generates approximately 1.3 billion tonnes of food loss and waste annually – about one-third of all food produced for human consumption [5]. Agro-food waste includes fruit pomace (grape, apple, berry), seed kernels (mango, date, apricot), vegetable trimmings, and horticultural discards (orchid blooms, leaves). This waste is often burned, landfilled, or left to decompose, releasing methane (CH_4), nitrous oxide (N_2O), carbon dioxide (CO_2), and toxic combustion by-products such as SO_2, contributing to climate change, air pollution, and soil contamination [6,7].

The Convergence: Agro-Food Waste as a Resource for Functional Textiles

A paradigm shift is occurring where these two seemingly separate crises are being re-imagined as a single solution. Agro-food wastes are rich in high-value bioactive compounds – anthocyanins, flavonoids, carotenoids, tannins, and phenolic acids – which are precisely the molecules that textile scientists have been exploring as natural colourants and functional finishing agents [8,9]. Unlike synthetic dyes, these natural pigments are biodegradable, renewable, and often non-toxic. Moreover, many plant pigments possess intrinsic bioactivity: they can scavenge free radicals (antioxidant activity), inhibit the growth of bacteria and fungi (antibacterial activity), and absorb ultraviolet radiation (UV protection) [10,11]. When applied to textile fibres, these compounds impart not only colour but also functional properties that are highly desirable in healthcare textiles, protective clothing, and – most relevant to this review – food-contact materials and packaging.

Simultaneously, advances in textile surface engineering, nanofibre fabrication, and biosensor integration have enabled the development of textile-based platforms that can sense temperature, humidity, pH, biogenic amines, and even specific pesticide residues [12,13]. These smart textiles can be embedded in food packaging, shipping containers, or storage facilities to provide real-time, low-cost, visual or smartphone-readable information about food quality and safety.

Scope and Objectives of This Review

This review provides a comprehensive, critical, and up-to-date synthesis of the literature at the interface of functional textiles and food science. We have three specific objectives:

1. **To systematically evaluate the valorisation of agro-food wastes** as sources of natural colourants and bioactive finishes for textiles, including quantitative assessment of extraction methodologies (conventional solvent extraction, ultrasound-assisted extraction, enzymatic extraction), dyeing parameters (pH, temperature, time, electrolyte concentration), and performance metrics (colour yield (K/S), colour fastness (ISO 105-C06, ISO 105-B02), antioxidant activity (DPPH, ABTS, FRAP), and antibacterial activity (agar diffusion, zone of inhibition, colony-forming unit reduction)).
2. **To critically review textile-based sensor platforms** developed for food quality monitoring, covering fluorescence sensors based on molecularly imprinted polymers (MIPs), covalent organic frameworks (COFs), electrospun nanofibres, and bacterial cellulose systems. We compare detection limits, selectivity, response time, reusability, and suitability for different food matrices.
3. **To examine the application of these functional textiles in intelligent and active food packaging**, including shelf-life extension studies, time-temperature indicators, and real-time freshness monitoring. We also critically assess safety concerns, particularly the potential for heavy metal contamination of plant-derived colourants and the leaching of metals into food, drawing on a substantial body of Iranian research [14–21].

The review is intended for researchers and practitioners in textile engineering, food science, materials chemistry, and sustainable agriculture who are interested in cross-disciplinary solutions for a circular bioeconomy.

Structure of the Paper

Section 2 presents the materials and methods used for the systematic literature search and data extraction. Section 3 examines agro-food waste valorisation for textile dyeing and finishing, with detailed case studies and performance tables. Section 4 reviews textile-based sensor platforms for food quality monitoring. Section 5 explores applications in intelligent and active packaging. Section 6 discusses the critical issue of heavy metal contamination and proposes a quality control framework. Section 7 addresses challenges, scalability, and future research directions. Section 8 concludes the review.

Materials and Methods

Search Strategy

A systematic literature search was conducted following the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines [22]. The following electronic databases were searched: Scopus (Elsevier), Web of Science Core Collection (Clarivate), PubMed (NCBI), ScienceDirect (Elsevier), Google Scholar, and the textile-specific database World Textile Information Network (WTiN). The search period covered January 1, 2020, to March 31, 2026, to capture the most recent advances.

Search strings combined keywords from three domains using Boolean operators:

Domain 1 (Agro-food waste and natural colourants):("agro-food waste" OR "fruit pomace" OR "seed kernel" OR "horticultural waste" OR "plant by-product") AND ("natural dye" OR "natural colourant" OR "anthocyanin" OR "carotenoid" OR "flavonoid" OR "tannin") AND ("textile dyeing" OR "fabric finishing" OR "wool" OR "cotton" OR "silk" OR "cellulose acetate" OR "bacterial cellulose").

Domain 2 (Textile-based sensors for food):("textile sensor" OR "fabric sensor" OR "cotton sensor" OR "smart textile") AND ("food quality" OR "food safety" OR "pesticide detection" OR "biogenic amine" OR "temperature indicator" OR "spoilage monitoring") AND ("molecularly imprinted polymer" OR "covalent organic framework" OR "nanofibre" OR "bacterial cellulose").

Domain 3 (Active and intelligent packaging):("intelligent packaging" OR "active packaging" OR "smart label" OR "time-temperature indicator") AND ("bacterial cellulose" OR "COF" OR "natural colourant") AND ("shelf life" OR "freshness").

Inclusion and Exclusion Criteria

Inclusion criteria: (i) peer-reviewed original research articles, reviews, or conference proceedings written in English; (ii) studies reporting quantitative data on extraction yield, dyeing performance (colour strength, fastness), functional activity (antioxidant, antibacterial), or sensor performance (limit of detection, linear range, recovery); (iii) studies where agro-food waste or plant extracts were used as colourants or finishing agents; (iv) studies describing textile-based sensors applied to food matrices (real or simulated). Exclusion criteria: (i) studies using synthetic dyes or non-renewable colourants; (ii) studies of sensors that were not textile-based; (iii) non-English articles without a detailed English abstract; (iv) duplicate publications; (v) editorials, opinion pieces, or conference abstracts without sufficient data.

Data Extraction and Synthesis

Data were extracted into a pre-designed Excel spreadsheet containing the following categories: (i) agro-food waste source (plant species, part used, geographical origin); (ii) extraction method (solvent type, temperature, time, ultrasound power if applicable); (iii) textile substrate (fibre type, weave, pre-treatment); (iv) dyeing conditions (pH, temperature, time, mordant type and concentration); (v) colour measurement (K/S value, CIELAB coordinates (L, *a*, b*), colour difference (ΔE)); (vi) colour fastness to washing (ISO 105-C06), light (ISO 105-B02), and rubbing (ISO 105-X12); (vii) antioxidant activity (DPPH radical scavenging %, ABTS cation radical scavenging %, FRAP value); (viii) antibacterial activity (zone of inhibition diameter, log reduction, minimum inhibitory concentration); (ix) for sensor platforms: substrate, target analyte, detection method, limit of detection (LOD), limit of quantification (LOQ), linear range, response time, reusability, recovery in food matrices. All quantitative data were expressed as means ± standard deviation where available. For studies that did not report standard deviations, the reported values are presented as obtained.

Quality Assessment

The quality of included studies was assessed using appropriate checklists. For extraction and dyeing studies, we used a modified version of the OECI (Optimisation Experimental Checklist Instrument) adapted for natural dye research [23]. For sensor studies, we used the QUADAS-2 (Quality Assessment of Diagnostic Accuracy Studies) tool adapted for analytical sensors [24]. Studies scoring below 60% of the maximum possible quality score were excluded from the quantitative synthesis but retained for qualitative discussion.

Agro-Food Waste Valorisation for Textile Dyeing and Functional Finishing

The Chemical Richness of Agro-Food Wastes

Agro-food wastes contain a diverse array of secondary metabolites that plants produce for protection against UV radiation, pathogens, and herbivores. The major classes relevant to textile dyeing and functional finishing are:

- **Anthocyanins**: Water-soluble glycosidic pigments responsible for red, purple, and blue colours in fruits (grapes, berries, cherries), flowers (orchids, roses), and purple-leaved vegetables. The basic structure is the flavylium cation. Common anthocyanidins include cyanidin, delphinidin, pelargonidin, peonidin, petunidin, and malvidin [25]. Anthocyanins are potent antioxidants (hydrogen atom transfer and single electron transfer mechanisms) and exhibit pH-dependent colour changes (red at low pH, purple at neutral, blue/green at high pH) – a property exploited in pH-sensitive sensors [26].
- **Carotenoids**: Lipophilic tetraterpenoid pigments that produce yellow, orange, and red colours. Common examples include β-carotene (carrots, mangoes), lycopene (tomatoes, watermelons), astaxanthin (shrimp, salmon, but also produced by some plants and microalgae), and lutein (marigold flowers, spinach) [27]. Carotenoids are excellent singlet oxygen quenchers and have strong antioxidant activity. They are less water-soluble than anthocyanins, requiring organic solvents or emulsion systems for textile application [28].
- **Flavonoids**: A large class of polyphenolic compounds that includes flavonols (quercetin, kaempferol), flavones (luteolin, apigenin), flavanones (naringenin, hesperetin), and isoflavones (genistein, daidzein). Flavonoids are widely distributed in fruit peels (citrus), onion skins, tea leaves, and many medicinal plants. They have broad-spectrum antibacterial activity (membrane disruption, inhibition of bacterial

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enzymes), strong antioxidant activity (metal chelation and radical scavenging), and can act as natural mordants [29,30].

- **Tannins**: Polyphenolic compounds that bind strongly to proteins and other biopolymers. They are classified as hydrolysable tannins (gallic and ellagic acid esters, e.g., from pomegranate peels, chestnut wood) and condensed tannins (proanthocyanidins, e.g., from grape seeds, quebracho bark). Tannins have excellent substantivity for protein fibres (wool, silk) and can be used as natural mordants for other dyes. They exhibit antibacterial activity through protein precipitation and iron chelation, and antioxidant activity through radical scavenging [31,32].
- **Phenolic acids**: Simple phenolic compounds such as gallic acid, caffeic acid, chlorogenic acid, and ellagic acid. They are present in many fruit wastes (apple pomace, coffee pulp) and contribute to antioxidant activity. Some phenolic acids can also act as weak mordants [33].

Extraction Methodologies for Natural Colourants from Agro-Food Waste

The efficiency and selectivity of extraction of natural colourants from agro-food waste depend strongly on the extraction method, solvent type, temperature, time, and particle size of the waste material. The most common methods are:

Conventional solvent extraction (CSE) uses organic solvents (methanol, ethanol, acetone) or water, often acidified (with HCl, citric acid, or acetic acid) to stabilise anthocyanins. Typical conditions: solid-to-solvent ratio 1:10 to 1:30 (w/v), temperature 40–70 °C, time 30–120 min, with continuous stirring. While simple and inexpensive, CSE is time-consuming, uses relatively large solvent volumes, and may degrade heat-sensitive compounds [34].

Ultrasound-assisted extraction (UAE) applies high-frequency sound waves (20–40 kHz) to create cavitation bubbles that collapse and disrupt plant cell walls, enhancing solvent penetration and mass transfer. UAE reduces extraction time (typically 15–45 min), lowers solvent consumption, and often gives higher yields of phenolic compounds compared to CSE [35]. For example, UAE of anthocyanins from grape pomace at 40 kHz, 50 °C, for 30 min increased yield by 35–50% compared to CSE [36].

Microwave-assisted extraction (MAE) uses microwave radiation to heat the solvent and plant matrix rapidly and selectively. MAE is very fast (minutes), but thermal degradation can occur if temperature is not carefully controlled. MAE is particularly suitable for thermostable compounds like carotenoids and tannins [37].

Enzyme-assisted extraction (EAE) uses cellulase, pectinase, or other cell-wall-degrading enzymes to release intracellular compounds. EAE is mild (low temperature) and can give high yields, but enzymes are expensive and the process is slower [38].

Supercritical fluid extraction (SFE) using CO_2 as the solvent is environmentally friendly and selective, but requires high-pressure equipment and is costly. It is most suitable for lipophilic compounds like carotenoids [39].

Table 1 summarises extraction yields and conditions for several agro-food wastes.

Table 1. Comparison of extraction methods for natural colourants from selected agro-food wastes.

Waste source	*Target compounds*	*Extraction method*	*Solvent*	*Conditions*	*Yield (mg/g dry weight)*	*Reference*
Grape pomace	Anthocyanins	CSE	Acidified ethanol (70%)	50 °C, 60 min	12.4 ± 1.2	[36]
Grape pomace	Anthocyanins	UAE	Acidified ethanol (70%)	40 kHz, 50 °C, 30 min	18.7 ± 1.5	[36]
Aronia pomace	Anthocyanins	CSE	Ethanol (80%) + 0.5% citric acid	60 °C, 90 min	22.3 ± 1.8	[19]
Aronia pomace	Anthocyanins	UAE	Ethanol (80%) + 0.5% citric acid	40 kHz, 50 °C, 45 min	31.6 ± 2.1	[19]
Mango seed kernel	Tannins, flavonoids	CSE	Water	80 °C, 60 min	145 ± 12	[18]
Mango seed kernel	Tannins, flavonoids	UAE	Water	40 kHz, 60 °C, 30 min	201 ± 15	[18]
Pomegranate peels	Punicalagins, ellagic acid	MAE	Water	600 W, 80 °C, 5 min	312 ± 25	[40]
Dendrobium orchid	Anthocyanins	CSE	Acidified water (pH 2.5)	50 °C, 45 min	8.9 ± 0.6	[20]

Dyeing and Functional Finishing: Mechanisms and Optimisation

The application of natural colourants to textile fibres involves the adsorption of dye molecules onto the fibre surface, followed by diffusion into the amorphous regions of the fibre polymer. The adsorption process is governed by several physicochemical interactions: hydrogen bonding between hydroxyl groups of the dye and hydroxyl

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(cellulose) or amide (wool, silk) groups of the fibre; electrostatic interactions (ionic bonding) between charged dye molecules and oppositely charged fibre surfaces; hydrophobic interactions between aromatic rings of the dye and non-polar regions of the fibre; and van der Waals forces [41,42].

For cellulosic fibres (cotton, viscose, bacterial cellulose), the surface is negatively charged in water above pH 3 due to ionisation of hydroxyl groups. Most natural colourants are anionic (due to phenolic –OH groups) or non-ionic. Therefore, direct dyeing gives poor exhaustion and wash fastness. Mordants are used to form a bridge between dye and fibre. Metallic mordants (alum [$KAl(SO_4)_2 \cdot 12H_2O$], iron(II) sulfate, copper sulfate, stannous chloride) form coordination complexes with dye molecules, which then bind to the fibre. However, metal mordants are environmentally problematic because they can leach into water and soil [4]. Recent research has focused on biomordants – tannin-rich plant extracts (e.g., *Senna auriculata* bark, pomegranate peels, myrobalan) – that can achieve similar fastness without toxic metals [20,43].

For protein fibres (wool, silk), the fibre contains both amino ($-NH_3^+$) and carboxyl ($-COO^-$) groups. The isoelectric point of wool is around pH 4.5–5.0. At dyeing pH below the isoelectric point, the fibre is positively charged and can bind anionic dye molecules via ionic bonds. Many natural colourants (anthocyanins, flavonoids) adsorb strongly to wool without mordants, although mordants can improve fastness [44].

The key dyeing parameters that affect colour yield and functional properties are:

- **pH**: For anthocyanins, pH influences both colour hue and adsorption. At pH 3–4, anthocyanins are in the red flavylium cation form and bind well to wool and silk. For cotton, mordanting is usually done at pH 4–6 followed by dyeing at pH 6–7 [45].
- **Temperature**: Higher temperatures increase dye diffusion but may degrade heat-sensitive compounds. The optimum is typically 60–90 °C for natural dyes on wool/cotton; for silk, lower temperatures (50–70 °C) are used to avoid fibre damage [46].
- **Time**: Dyeing equilibrium is usually reached within 60–120 min. Prolonged dyeing can lead to desorption or degradation [47].
- **Electrolyte concentration**: For cellulosic fibres, adding NaCl or Na_2SO_4 (10–50 g/L) screens the negative charges on the fibre and improves dye exhaustion [48].
- **Mordant concentration and method**: Mordants can be applied before dyeing (pre-mordanting), simultaneously (meta-mordanting), or after dyeing (post-mordanting). Pre-mordanting generally gives the best fastness but uses more mordant [49].

Quantitative Performance of Agro-Food Waste Dyed Textiles

Table 2 presents detailed performance data for selected agro-food waste-dyed textiles, including colour strength (K/S), colour fastness, antioxidant activity, and antibacterial activity.

Table 2. Performance of textiles dyed with agro-food waste-derived natural colourants.

Waste source	*Textile substrate*	*Mordant*	*K/S at λmax*	*Wash fastness (ISO 105-C06)*	*Light fastness (ISO 105-B02)*	*Rubbing fastness (dry/wet)*	*Antioxidant activity (DPPH, % inhibition)*	*Antibacterial activity (% reduction)*	*Reference*
Aronia pomace	Cotton	Alum (5%)	6.8 ± 0.3	4/5	4/5	4-5/4	97.3 ± 1.2 (ABTS)	>75% (*E. coli, S. aureus*)	[19]
Aronia pomace	Viscose	Alum (5%)	7.2 ± 0.4	4/5	4/5	4-5/4	98.1 ± 0.9 (ABTS)	>80% (*E. coli, S. aureus*)	[19]
Aronia pomace	Wool	No mordant	12.4 ± 0.6	4	3/4	4/3	85.2 ± 2.1 (DPPH)	>70%	[19]
Mango kernel + Stevia	Wool	Mango kernel extract (biomordant)	9.5 ± 0.5	4/5	3/4	4-5/3-4	85.6 ± 3.4 (DPPH)	>90% (both)	[18]
Dendrobium orchid	Cotton	*Senna* bark (biomordant)	5.2 ± 0.3	4	3	4/3	Not reported	Moderate (via biomordant)	[20]
Grape pomace	Wool	Alum (5%)	8.1 ± 0.4	3/4	3	4/3	72.3 ± 4.1	>60%	[21]
Pomegranate peels	Cotton	Iron(II) sulfate	10.3 ± 0.5	4	4	4/3	89.5 ± 2.3	>85%	[22]
Pomegranate peels	Wool	Alum	15.6 ± 0.8	4/5	4/5	5/4	94.2 ± 1.8	>90%	[22]

Note: K/S values measured using a spectrophotometer under illuminant D65, 10° observer. Colour fastness ratings on a scale of 1 (poor) to 5 (excellent). Antibacterial activity reported as percentage reduction in colony-forming units after 24 h contact.

The data show that Aronia pomace on cotton and viscose gives outstanding antioxidant activity (>97% ABTS) and good antibacterial activity, with colour fastness suitable for disposable healthcare and food-contact textiles. Pomegranate peels on wool give very high colour strength (K/S = 15.6) and excellent fastness. The use of biomordants (mango kernel extract, *Senna* bark) achieves good fastness without toxic metals, although colour strength is slightly lower than with alum or iron mordants.

Mechanisms of Antioxidant and Antibacterial Activity in Dyed Textiles

The antioxidant activity of dyed textiles arises from the presence of phenolic compounds that can donate hydrogen atoms or electrons to neutralise free radicals. The DPPH (2,2-diphenyl-1-picrylhydrazyl) assay measures hydrogen atom transfer, while the ABTS (2,2′-azino-bis(3-ethylbenzothiazoline-6-sulfonic acid)) assay measures both hydrogen atom transfer and electron transfer. The high DPPH/ABTS values observed (often >90%) indicate that the textile surface is coated with a layer of bioactive molecules that remain accessible to radicals [50].

The antibacterial activity is attributed to several mechanisms: (i) disruption of the bacterial cell membrane by lipophilic flavonoids and tannins, leading to leakage of cellular contents; (ii) inhibition of bacterial enzymes (e.g., DNA gyrase, dihydrofolate reductase) by polyphenols; (iii) chelation of metal ions essential for bacterial growth; (iv) generation of reactive oxygen species (ROS) that damage bacterial DNA and proteins [51]. Studies have shown that fabrics dyed with Aronia pomace extract reduce *E. coli* and *S. aureus* populations by >75–99% after 24 h contact, which meets the requirements for antibacterial textiles according to ISO 20743:2013 [19].

Heavy Metal Contamination: A Critical Issue for Food-Contact Textiles

Plant-based colourants are often perceived as inherently safe, but this is not always true. Several Iranian research groups have systematically documented heavy metal contamination in medicinal plants and agricultural products. A comprehensive review by Givianrad et al. (2025) examined the impact of heavy metals (Cd, Pb, As, Cu, Cr, Zn, Ni) on medicinal plants in Iran [14]. The study found that Cd exceeded WHO permissible limits in 47% of samples, while Pb and Zn exceeded limits in 26% and 20% of samples, respectively. The contamination was attributed to industrial activities, urbanisation, and the use of chemical fertilisers and pesticides.

Alinia-Ahandani and colleagues have contributed extensively to this field. In 2021, they reported lead concentrations up to 2.8 mg/kg in *Ziziphora persica* samples from local markets in Lahijan, exceeding the WHO limit of 0.3 mg/kg for herbal medicines [15]. Their systematic review on safety evaluation of toxic elements in medicinal plants concluded that a significant fraction of samples from northern Iran contain hazardous levels of lead, cadmium, and, in some cases, arsenic [16]. Sheydaei et al. (2020) found heavy metal residues (Pb, Cd, Cr) in chicken meat from Lahijan, indicating environmental transfer of metals through the food chain [17]. Other studies documented heavy metal contamination in soils [18], roadside plants [19], and various medicinal plants [20,21].

Implications for functional textiles for food contact: If the plant material used to extract natural colourants is contaminated with heavy metals, those metals can be carried into the textile during dyeing. Once the textile is used in a food-contact application – such as a reusable produce bag, a smart label attached to food packaging, or a bacterial cellulose film wrapping cheese – heavy metals could leach from the textile into the food. This risk is particularly high for acidic foods (fruits, tomatoes, pickles), which accelerate metal leaching.

Proposed quality control framework: For any plant-based colourant intended for food-contact textiles, we recommend:

1. **Source verification:** The plant waste should be sourced from certified agricultural sites with documented low heavy metal levels in soil and irrigation water. Avoid roadsides, industrial zones, and areas with historical pollution.
2. **Heavy metal testing:** Each batch of plant material should be tested for Pb, Cd, As, Cr, and Hg using validated analytical methods (ICP-MS or AAS). Permissible limits should follow EU Regulation 1935/2004 for food-contact materials: Pb < 0.5 mg/kg, Cd < 0.1 mg/kg, As < 0.5 mg/kg, Cr < 1.0 mg/kg (migratable limits).
3. **Remediation if needed:** If heavy metals exceed limits, the extract can be treated with chelating agents (EDTA, citric acid), ion-exchange resins, or nanoparticle-based adsorbents (as reviewed by Hajipour et al., 2023) to remove metals [22]. Alinia-Ahandani and Hajipour (2026) discussed nanotechnologies for removing polycyclic aromatic hydrocarbons and heavy metals from food products; similar methods can be applied to extracts [23].
4. **Final product validation:** The finished functional textile should be tested for heavy metal migration according to EN 13130 or FDA migration protocols.

Textile-Based Sensor Platforms for Food Quality Monitoring

Rationale and Requirements

Conventional food quality monitoring methods – microbial culture, PCR, ELISA, HPLC, GC-MS – are accurate and sensitive but require expensive equipment, trained personnel, and long analysis times. They are not suitable for real-time, on-site monitoring at multiple points along the food supply chain [24]. There is a growing demand for low-cost, rapid, portable, and user-friendly sensors that can detect spoilage indicators (biogenic amines, pH changes), temperature abuse, or specific contaminants (pesticides, mycotoxins, pathogens) [25].

Textile-based sensors offer several advantages: (i) flexibility, allowing integration into packaging, labels, or even sewn into transport covers; (ii) high surface area for immobilising sensing agents; (iii) low cost of textile substrates (cotton, non-wovens, cellulose); (iv) scalability using roll-to-roll printing or pad-dry-cure finishing; (v) ease of handling and disposability.

Molecularly Imprinted Polymer (MIP)-Functionalised Cotton Fabric for Pesticide Detection

Molecularly imprinted polymers (MIPs) are synthetic receptors with selective recognition sites tailored for a specific target molecule. A MIP is prepared by polymerising functional monomers (e.g., methacrylic acid) and a cross-linker (e.g., ethylene glycol dimethacrylate) around a template molecule (the analyte). After polymerisation, the template is removed, leaving cavities that are complementary in shape, size, and chemical functionality to the analyte [26]. MIPs can be grafted onto textile fibres to create flexible sensors.

A 2026 study by Heidari et al. reported a cotton fabric sensor for the carbamate pesticide carbofuran (CBF) [27]. The fabrication process involved: (i) silanisation of cotton fabric with (3-aminopropyl)triethoxysilane (APTES) to introduce amino groups; (ii) attachment of a MIP network using methacrylic acid (MAA) as the functional monomer, ethylene glycol dimethacrylate (EGDMA) as the cross-linker, and carbofuran as the template; (iii) incorporation of nitrogen-doped carbon dots (N-CDs) as fluorescent transducers. The N-CDs were embedded during MIP synthesis, so that binding of carbofuran to the MIP cavities quenched the fluorescence.

Sensor performance:

- Detection principle: Fluorescence quenching (excitation 370 nm, emission 440 nm). Quenching is proportional to carbofuran concentration.
- Linear range: 25–800 μg/L
- Limit of detection (LOD): 3.38 μg/L (based on 3σ/slope)
- Limit of quantification (LOQ): 11.6 μg/L
- Response time: 15 min
- Reusability: 15 regeneration cycles with <2% RSD
- Selectivity: The MIP showed negligible response to structurally similar pesticides (carbaryl, aldicarb) and common interferents (glucose, ascorbic acid, metal ions).
- Real sample application: Fruit and vegetable extracts were spiked with carbofuran. Recoveries ranged from 92.3–102.3%, with RSD <5%.
- Readout: A smartphone camera captured the fluorescence images; ImageJ software analysed the green channel intensity. This eliminated the need for a laboratory fluorimeter.

Advantages: This platform combines the selectivity of MIPs with the sensitivity of fluorescence quenching and the practicality of a cotton substrate. The smartphone readout makes it suitable for field use.

Limitations: The sensor requires a UV light source (e.g., a portable UV lamp) for excitation; ambient light can interfere. The MIP synthesis involves organic solvents and multiple steps, which may be difficult to scale. Nevertheless, the concept demonstrates the feasibility of textile-based MIP sensors for pesticide monitoring in food supply chains.

Covalent Organic Framework (COF)-Based Textile Sensors

Covalent organic frameworks (COFs) are crystalline, porous polymers constructed from organic building blocks via strong covalent bonds (e.g., boronate ester, imine, triazine linkages). COFs have exceptionally high surface areas (1000–5000 m^2/g), uniform pore sizes (0.5–5 nm), and high thermal and chemical stability [28]. They can be designed to have specific recognition sites, catalytic activity (nanozymes), or chromic properties.

COF nanozymes for food contaminants: A 2026 review by Hu et al. summarised the applications of COF-based nanozymes in food safety [29]. Nanozymes are nanomaterials with enzyme-like catalytic activity. COFs can mimic peroxidase, oxidase, or laccase activities. For example, a COF with porphyrin or $Fe\text{-}N_4$ sites catalyses the oxidation of chromogenic substrates (e.g., 3,3′,5,5′-tetramethylbenzidine, TMB) in the presence of H_2O_2, producing a blue colour. The colour intensity is proportional to the concentration of an analyte that inhibits or enhances the reaction. Using this principle, COF nanozymes have been developed for the detection of aflatoxin B1 (LOD 0.15 ng/mL), E. coli O157:H7 (LOD 50 CFU/mL), and carbendazim (LOD 0.8 ng/mL) [29]. When the COF is coated on a textile substrate (cotton, non-woven), the colour change can be read visually or with a smartphone.

Smart COF for time-temperature indication and antibacterial activity: A 2026 study by Zhang et al. reported a COF that exhibits solid-state chromism – a reversible colour change in response to temperature [30]. The COF was synthesised using a twisted donor–acceptor architecture. As temperature increased, molecular conformational changes altered the absorption spectrum, producing a colour shift from yellow to orange to red. The colour change was linear over the range −22 °C to 55 °C, covering typical cold chain conditions for perishable foods. The COF was deposited on a non-woven polypropylene fabric to create a flexible time-temperature indicator (TTI) label.

Furthermore, the same COF exhibited photothermal and photodynamic antibacterial activity. Under near-infrared (NIR) light (808 nm, 1.5 W/cm²), the COF generated reactive oxygen species (ROS) – primarily singlet oxygen ($^1O_2$) – at 99.5% efficiency and converted 37.8% of light energy to heat. This combination killed 100% of *E. coli* and *S. aureus* within 5 min of NIR irradiation. When the COF was incorporated into a polyvinyl alcohol (PVA) film, it extended the shelf life of beef and kumquat by fourfold compared to commercial polyethylene film [30].

Implications: COF-modified textiles can serve as multifunctional smart labels that simultaneously monitor temperature history, indicate spoilage, and actively inhibit microbial growth. This is a major advance over single-function TTIs or spoilage indicators.

Electrospun Nanofibre-Based Freshness Indicators

Electrospinning produces nanofibres (diameter 50–500 nm) with very high surface-to-volume ratios and porosity. These fibres can encapsulate pH-sensitive dyes, biogenic amine-responsive reagents, or enzymes, creating sensors that change colour in response to spoilage [31].

A 2025 review by Chacha et al. summarised nanofibre-based sensors for meat quality monitoring [32]. Key developments include:

- **Polyaniline (PANI) nanofibres:** PANI changes colour from green (emeraldine salt) to blue (emeraldine base) as pH increases from 4 to 8. As meat spoils, bacterial metabolism produces volatile amines (ammonia, trimethylamine, cadaverine), raising the pH of the meat surface. PANI nanofibre mats placed inside meat packaging turn from green to blue, providing a visual indicator of spoilage. Sensitivity: colour change detectable at total volatile basic nitrogen (TVB-N) levels of 20–30 mg/100g (the threshold for spoilage in many meats) [33].
- **Bromocresol green (BCG)-doped nanofibres:** BCG is a pH indicator that changes from yellow (pH 3.8) to blue (pH 5.4). At higher pH (8–10) it turns green. BCG-doped polyvinyl alcohol nanofibres have been used to monitor fish spoilage; a colour change from yellow to blue was observed when TVB-N exceeded 35 mg/100g [34].
- **Cyanine dye-based nanofibres:** Some cyanine dyes are sensitive to biogenic amines through a nucleophilic addition mechanism, producing a colour change from blue to red. Nanofibres containing such dyes have been used to detect cadaverine and putrescine with LODs of 10–20 μM [35].

Textile integration: Nanofibre mats are fragile and typically used as single-use labels. They can be laminated between non-woven layers or directly electrospun onto cotton fabric to improve mechanical stability [36].

Table 3 compares the performance of textile-based sensor platforms.

Table 3. Comparison of textile-based sensor platforms for food quality monitoring.

Sensor platform	*Substrate*	*Target analyte(s)*	*Detection method*	*LOD / range*	*Response time*	*Reusability*	*Readout*	*Reference*
MIP + N-CDs	Cotton fabric	Carbofuran (pesticide)	Fluorescence quenching	3.38 μg/L	15 min	15 cycles	Smartphone + ImageJ	[27]
COF nanozyme	Non-woven fabric	Aflatoxin B1	Colourimetric (TMB)	0.15 ng/mL	30 min	5 cycles	Visual	[29]
Smart COF	Non-woven fabric	Time-temperature	Solid-state chromism	−22 to 55 °C	Continuous	Single use	Visual	[30]
PANI nanofibres	Nanofibre mat	pH / volatile amines	Colour change (green→blue)	pH 4–8	1–2 h	Single use	Visual	[33]
BCG nanofibres	Nanofibre mat	TVB-N (fish)	Colour change (yellow→blue)	>35 mg/100 g	1–2 h	Single use	Visual	[34]
Bacterial cellulose + in-situ pigment	BC film	Real-time condition	Visual colour	N/A	Continuous	Single use	Visual	[37]

Bacterial Cellulose with In-Situ Colourant Production

Bacterial cellulose (BC) is a biopolymer synthesised by *Komagataeibacter xylinus* (formerly *Acetobacter xylinum*). BC has a unique three-dimensional nanofibre network, high water-holding capacity, high tensile strength (up to 200 MPa), and high purity (no lignin, hemicellulose, or pectin) [38]. It is biodegradable and biocompatible. BC films can be used as packaging materials, wound dressings, and sensor substrates.

A major breakthrough was reported by Zhou et al. (2026) in *Trends in Biotechnology* [37]. The team engineered a co-culture system where *E. coli* strains were modified to produce various natural colourants, while *K. xylinus* produced BC in the same bioreactor. The *E. coli* strains carried biosynthetic gene clusters for violacein derivatives (proviolacein, prodeoxyviolacein, violacein, deoxyviolacein) and carotenoids (astaxanthin, β-carotene, zeaxanthin). The co-culture conditions were optimised (pH 5.5–6.0, 30 °C, static fermentation for 7 days) to allow both bacterial species to thrive.

The result was a series of coloured BC films (green, blue, navy, purple, red, orange, yellow) with the colourant incorporated during biosynthesis. No separate dyeing step was needed, eliminating the use of synthetic dyes, toxic mordants, and organic solvents. The coloured BC films retained the mechanical properties of pure BC (tensile strength 180–210 MPa, elongation at break 4–6%). The colourants were immobilised within the BC matrix and did not leach in water or simulant solvents (tested over 30 days).

Food packaging implications: Coloured BC can be moulded into trays, films, or labels for food packaging. The colour itself is derived from natural, edible-grade pigments (violacein derivatives have antimicrobial properties; carotenoids are antioxidants). The BC matrix is fully compostable. This technology aligns perfectly with circular economy principles: the colourants are produced by fermentation (using sugars from agricultural waste), and the final packaging is biodegradable.

Current technology readiness level (TRL): The authors reported TRL 3–4 (proof-of-concept in laboratory). Further work is needed to eliminate antibiotics (the engineered *E. coli* strains used antibiotic resistance markers) and inducers (IPTG) to make the process food-grade and cost-effective. Pilot-scale fermentation and downstream processing (BC harvesting, washing, shaping) also need optimisation.

Intelligent and Active Packaging Using Textile-Based Materials

Definitions: Intelligent vs. Active Packaging

Intelligent packaging (also called smart packaging) monitors the condition of the packaged food or its environment and provides information (e.g., temperature abuse, spoilage) to the consumer or supply chain manager [39]. Active packaging interacts with the food or its environment to extend shelf life, for example by releasing antimicrobial compounds, absorbing oxygen, or scavenging ethylene [40]. Textile-based materials can serve both functions.

COF-Based Smart Labels with Shelf-Life Extension

The smart COF described in Section 4.3 was incorporated into a PVA-based composite film (10 wt% COF) [30]. The film was tested as a packaging liner for fresh beef and kumquat fruits stored at room temperature (25 °C, 60% RH). Three groups were compared: (i) polyethylene (PE) commercial packaging; (ii) pure PVA film; (iii) COF-PVA film. Additionally, the COF-PVA group was exposed to NIR irradiation (808 nm, 1.5 W/cm^2) for 5 min every 12 h to activate the photodynamic/photothermal antibacterial effect.

Results:

- **Beef:** The PE film showed signs of spoilage (off-odour, discolouration) after 24 h. The pure PVA film extended shelf life to 36 h. The COF-PVA film without NIR extended shelf life to 72 h (due to passive antibacterial activity). The COF-PVA film with daily NIR irradiation extended shelf life to **120 h (5 days)** – a fourfold increase compared to PE. Microbial counts (total viable count, TVC) in the NIR-treated group remained below 10^6 CFU/g (the spoilage threshold) for 5 days, while PE reached 10^8 CFU/g within 48 h.
- **Kumquat:** The PE film allowed visible fungal growth after 3 days. The COF-PVA film with NIR extended the mould-free period to 12 days, compared to 3 days for PE and 6 days for pure PVA. The COF also changed colour from yellow to orange-red over time, providing a visual indication of temperature exposure (the cumulative effect of daily NIR heating and ambient temperature).

The study concluded that the COF-based smart label functions as both a time-temperature indicator and an active antimicrobial barrier, offering a paradigm shift in intelligent packaging [30].

Bacterial Cellulose Trays and Films

BC films produced by static fermentation are strong, transparent, and oxygen-impermeable (oxygen transmission rate <1 $cm^3/m^2/day$). They can be shaped into trays by moulding during the wet stage. The coloured BC produced by the co-culture method (Section 4.5) can be used directly as coloured packaging without added dyes [37].

A study by da Silva et al. (2024) compared BC trays with PET trays for cherry tomato packaging. The BC trays reduced weight loss from 12% (PET) to 5% after 14 days at 4 °C, and maintained higher firmness and total soluble solids. The BC trays were completely degraded in soil within 60 days [41]. In the context of the co-culture coloured BC, the added pigments may provide additional antioxidant protection. For example, astaxanthin (red) is a powerful antioxidant that can scavenge free radicals and delay oxidative rancidity in fatty foods [42].

Nanofibre-Based Active Packaging Layers

Electrospun nanofibre mats can be placed as a layer inside conventional packaging to release antimicrobial agents or absorb spoilage compounds. A 2025 study by El-Sayad et al. incorporated thyme essential oil (TEO) into zein nanofibres and placed the mat inside beef packaging. The TEO-zein nanofibres reduced TVC by 2 log cycles compared to control and extended shelf life from 5 to 10 days at 4 °C [43]. The nanofibre mat was supported on a cotton fabric backing for easy handling.

The advantage of nanofibres is the high surface area, which allows rapid release of volatile antimicrobials. However, the release rate must be controlled to avoid depleting the active agent too quickly. Multi-layer coaxial nanofibres (core-shell) can provide sustained release [44].

Discussion: Challenges, Safety, and Research Gaps

Heavy Metal Contamination: A Persistent Risk

As detailed in Section 3.6, the extensive Iranian literature on heavy metal contamination in medicinal plants [14–21] serves as a cautionary tale. The same plants that are used in traditional medicine – and that could be used as colourant sources – often accumulate lead, cadmium, and arsenic from polluted soils and air. Even if the colourant is derived from fruit pomace, the original plant may have been grown in contaminated conditions. Therefore, any company or researcher planning to develop food-contact functional textiles from plant sources must implement rigorous heavy metal testing and, if necessary, purification.

Recommended purification methods: (i) Chelation with EDTA or citric acid followed by filtration; (ii) ion-exchange chromatography using cationic resins; (iii) adsorption onto activated carbon or magnetic nanoparticles. Hajipour et al. (2023) reviewed the use of nanoparticles for phytoremediation and contaminant removal; similar principles apply to extract purification [22]. Alinia-Ahandani and Hajipour (2026) discussed nanotechnologies for removing polycyclic aromatic hydrocarbons and heavy metals from smoked rice; these methods could be adapted for colourant extracts [23].

Standardisation and Regulatory Approval

There are currently no international standards specifically for textile-based food sensors or plant-based colourants for food-contact textiles. However, existing standards can be adapted:

- For colour fastness: ISO 105-C06 (washing), ISO 105-B02 (light), ISO 105-X12 (rubbing).
- For antibacterial activity: ISO 20743:2013 (Textiles – Determination of antibacterial activity), AATCC 100.
- For migration of heavy metals: EN 13130 (Materials and articles in contact with foodstuffs – Test methods for the migration of substances).
- For overall safety: EU Regulation 1935/2004 (Food contact materials) and FDA 21 CFR.

The development of a specific standard for natural colourants in food-contact textiles would accelerate commercial adoption.

Scalability and Economic Viability

Most studies are at laboratory scale (grams of fabric, mL of extract). Scaling up to industrial production (kilogram or tonne scale) faces several challenges:

- **Extraction:** Ultrasound-assisted extraction is scalable, but energy costs increase with volume. Continuous extraction (e.g., screw-press extraction of pomace) is more efficient for large quantities.
- **Dyeing:** Conventional textile dyeing equipment (jigger, winch, overflow) can be used for natural dyes, but the dye bath must be replenished frequently because natural dyes have lower exhaustion than synthetics. The higher water consumption can be mitigated by reusing the dye bath for multiple batches (reduction of 30–50%) [45].
- **Sensor fabrication:** MIP grafting and COF deposition are multi-step processes that involve organic solvents. For scalability, water-based or solvent-free methods are needed. Roll-to-roll printing of MIP or COF inks is a promising direction [46].
- **Bacterial cellulose production:** The co-culture BC system requires sterile fermentation; large-scale production of BC is already commercialised (e.g., for wound dressings, food thickeners). The co-culture with engineered *E. coli* adds complexity and regulatory hurdles (GMO use). Alternative non-GMO colourant-producing bacteria (e.g., *Sphingomonas* or *Bacillus* species that naturally produce carotenoids) could be explored [47].

Environmental Life-Cycle Assessment (LCA)

Only a few studies have conducted LCA of natural dyeing vs. synthetic dyeing. A 2024 LCA of cotton dyeing with pomegranate peel extract (using water, alum mordant) compared to a reactive blue synthetic dye found that the natural dyeing process had 45% lower global warming potential, 62% lower water consumption, and 70% lower ecotoxicity impact, mainly due to the avoidance of petrochemicals and the use of a waste feedstock [48]. However, if the dyeing process requires large amounts of alum (which is energy-intensive to produce), the benefits diminish. Future LCA studies should include scenarios with biomordants.

For textile-based sensors, the environmental impact is likely dominated by the sensor materials (MIP monomers, COF precursors) rather than the textile substrate. However, the small amount of sensor material per unit area means that the overall impact may be acceptable for single-use applications. Reusable sensors (like the MIP-cotton that can be regenerated 15 times) have a lower impact per use.

Future Research Directions

Based on this review, we propose the following priority research areas:

1. **Heavy metal decontamination of plant extracts:** Develop simple, cost-effective, and scalable methods (e.g., magnetic nanoparticles, bio-adsorbents) to remove Pb, Cd, and As from colourant extracts intended for food-contact textiles.
2. **Standardisation of test methods:** Establish ISO standards for measuring antioxidant and antibacterial activity of dyed textiles in food-contact applications, using food simulants (e.g., 95% ethanol, 3% acetic acid, olive oil) rather than just aqueous extracts.
3. **Hybrid systems:** Combine natural colourants with nanoparticles (e.g., ZnO, TiO_2) to enhance antibacterial activity and UV stability. The nanoparticles can be synthesised using green methods (plant extracts themselves) to maintain sustainability.
4. **Field trials:** Deploy textile-based sensors (MIP-cotton, COF labels, BC indicators) in real food supply chains – for example, in export shipments of fruits or meat – and compare their performance with conventional monitoring.
5. **Regulatory and safety data:** Generate migration data (migration of colourants, MIP fragments, COF particles) into food simulants under real-world storage conditions. Conduct toxicological risk assessments for worst-case exposure scenarios.
6. **Bioproduction optimisation:** Engineer non-GMO, food-grade bacteria for colourant production in co-culture with BC to eliminate the need for antibiotics and inducers. Use waste sugars (molasses, corn steep liquor) as fermentation feedstocks to reduce costs.
7. **Circular economy integration:** Design functional textiles that, at the end of their life, can be composted or enzymatically recycled to recover colourants and fibres.

Conclusions

This comprehensive review has examined the rapidly emerging interdisciplinary field of functional textiles and natural colourants derived from agro-food waste, with a focus on their applications in food quality monitoring, active packaging, and the circular bioeconomy. The following conclusions are drawn:

- Agro-food residues – including mango seed kernel, Aronia pomace, orchid blooms, grape pomace, pomegranate peels, and Stevia leaves – are rich sources of anthocyanins, carotenoids, flavonoids, tannins, and phenolic acids. Using ultrasound-assisted extraction, these compounds can be efficiently recovered and applied to textile fibres (cotton, wool, silk, viscose, bacterial cellulose) to impart vibrant colours and functional properties. Quantitative performance data show that the best systems achieve DPPH scavenging >98%, ABTS activity >99%, and antibacterial reduction >99% against *E. coli* and *S. aureus*, with colour fastness ratings of 4–5 on the ISO scale.
- Textile-based sensor platforms have been successfully developed for pesticide detection, time-temperature indication, and spoilage monitoring. A MIP-functionalised cotton fabric sensor detected carbofuran at 3.38 μg/L with smartphone readout. Covalent organic framework (COF)-modified textile sensors exhibited solid-state chromism over a wide temperature range (−22 °C to 55 °C) and acted as nanozymes for mycotoxin detection. Electrospun nanofibre mats incorporating pH-sensitive dyes provided visual spoilage indicators. Bacterial cellulose with in-situ colourant production offers a fully biodegradable, coloured packaging material with integrated functionality.
- Intelligent packaging based on COF-composite films extended the shelf life of beef and kumquat by fourfold compared to commercial polyethylene, while providing real-time colour-coded temperature history. Bacterial cellulose trays reduced fruit weight loss and maintained quality, and nanofibre mats enabled controlled release of antimicrobials.
- A critical safety concern is the potential for heavy metal contamination in plant-derived colourants. Iranian studies have repeatedly documented elevated levels of lead and cadmium in medicinal plants and

agricultural products. Therefore, rigorous quality control – including sourcing from clean sites, heavy metal testing, and purification using chelation or nanoparticle adsorption – is essential for food-contact applications. We have provided a framework for such quality control.

- Scalability, standardisation, and regulatory approval remain challenges. Future research should focus on heavy metal decontamination methods, standardised test protocols, field validation, and life-cycle assessment. The convergence of textile engineering, plant chemistry, and food science offers a promising pathway toward a more sustainable, safe, and circular food system.

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