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International Journal of Avian & Wildlife Biology

Research Article
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Coastal plant biomass as a resource for nanotechnology and materials engineering in sustainable applications

Volume 9 Issue 3 - 2025

Merve Arabacı,[1] Şahane Funda Arslanoğlu[2]
[1]Chemical Engineering Department, Faculty of Engineering, Ondokuz Mayıs University, Samsun
[2]Field Crops Department, Faculty of Agriculture, Ondokuz Mayıs University, Samsun

Correspondence: Dr. Merve ARABACI, Ondokuz Mayıs University, Department of Chemical Engineering, Turkey, Tel +905452571251

Received: November 28, 2025 | **Published:** December 19, 2025

Abstract

This review focuses on the application potentials of Medicinal-Aromatic Plants (TAB) selected from the Atakum coastal forest flora in terms of chemical and materials engineering. Extraction-separation processes (supercritical CO_2, microwave/ultrasound-assisted methods and deep eutectic solvents, DES), natural polymer sources (mucilage, pectin, lignocellulosic fraction), biocomposite and bioplastic development (especially CNF/CNC-reinforced PLA), electrospun nanofiber-based wound dressings/coatings, green corrosion inhibitors, active packaging and encapsulation technologies constitute the general framework of the article. Through the plant→compound→function mapping, Arum, Borago, Trachystemon, Galium, Fumaria, Helleborus, Ruscus and Crocus species were re-evaluated on the basis of technical feasibility along with toxicity and regulatory aspects. The study presents a roadmap with the perspectives of scalable process design, standardization (ASTM/ISO), LCA and TRL; discusses the sustainability of local bio-based product development (packaging, coatings, dermocosmetics, biomedical). Among the coastal forest species evaluated in this review, *Trachystemon orientalis* emerged as the strongest candidate for hydrogel and wound-dressing applications due to its high mucilage content and pectin-like hydrophilic polysaccharides. *Galium aparine*, characterized by its notable cellulose and hemicellulose composition, shows strong potential for biocomposite production and nanofiber reinforcement. *Borago officinalis* is rich in phenolic compounds, supporting its use in active food packaging and antioxidant coating technologies. *Arum maculatum*, with its starch content and gel-forming capacity, may be suitable for biopolymer and film development. Additionally, the carotenoid pigments identified in *Crocus* species provide evidence for applications in UV-protective materials and smart packaging systems. Together, these findings indicate that the coastal medicinal and aromatic plants of the Atakum region offer not only ethnobotanical value but also sustainable and high-potential biological resources for materials engineering, nanotechnology, and biopolymer research.

Keywords: medicinal and aromatic plants, nanotechnology, sustainable materials, biopolymers and nanocomposites,plant-based biomass

Introduction

Coastal forest ecosystems contain a rich diversity of medicinal and aromatic plants, yet their potential roles in materials engineering and bio-based technologies remain insufficiently explored. Ethnobotanical research on *Trachystemon orientalis*, *Arum maculatum*, *Galium aparine*, *Borago officinalis*, and *Crocus* spp. is well documented. However, the literature still lacks a comprehensive synthesis linking their botanical and phytochemical characteristics to advanced applications, including biopolymer development, hydrogels, nanofibers, active packaging, and biofunctional coatings.This gap limits the scientific understanding of how these species can contribute to emerging material innovations, particularly within a sustainability framework. Addressing this deficiency is essential, as many of these plants—especially those rich in mucilage, starch, cellulose, hemicellulose, or carotenoid pigments—exhibit properties aligned with current research trends in green materials science.

Previous studies have often focused on traditional medicinal uses or isolated chemical constituents, but they rarely integrate these findings with engineering-oriented perspectives. For example, *T. orientalis* is known to contain substantial mucilage (up to 11–14% dry weight) (Gülcemal & Alp, 2019) , yet its implications for hydrogel formulation, controlled-release systems, or biomedical dressings remain largely unexplored. Similarly, *A. maculatum* has documented starch contents ranging between 20–25% (Dogan et al., 2014), along with calcium oxalate crystals and phenolic derivatives; however, the potential of these components for biodegradable film production or polymer reinforcement is understudied. *G. aparine* offers significant lignocellulosic structures that could support biocomposite development, yet this relationship has not been systematically evaluated. The lack of such integrative analyses highlights a clear literature gap.

Furthermore, current reviews do not justify why specific regional plant lists are necessary for technological exploration. The Atakum coastal zone represents a unique microclimate where moisture, shade, and organic-rich soils promote high mucilage- and starch-accumulating species. Evaluating these plants collectively allows for a comparative perspective on their material-related attributes. A structured assessment also prevents speculative interpretations by grounding technological implications in measurable phytochemical and functional properties.

This study therefore compiles existing botanical, ecological, and phytochemical knowledge on selected coastal forest species; synthesizes their known material-related characteristics; and critically evaluates their relevance to engineering applications using available evidence. By integrating quantitative data such as mucilage yield, starch composition, and phenolic content with documented mechanical, rheological, or functional outcomes, this review establishes a scientifically robust basis for future experimental research. Additionally, considerations related to sustainable collection, cultivation, and management—particularly for toxic or endemic species—are included to ensure that potential applications align with ecological and ethical standards.

The Black Sea Region—especially Samsun's Atakum district—offers a concentrated representation of this biodiversity. Characterized by its humid coastal forests, hilly landscapes, seasonal streams, and fertile soils, the area acts as a natural corridor for plant distribution. These ecosystems, shaped by the interaction of maritime climate and varied topography, host unique microhabitats suitable for MAPs.

This study provides an in-depth analysis of nine medicinal and aromatic plant species identified within these landscapes, each recognized in both traditional knowledge systems and modern research for their therapeutic, toxicological, and technological attributes: *Arum maculatum* (Lords-and-Ladies), *Arum elongatum* (Elongated Arum), *Borago orientalis* (Eastern Borage), *Trachystemon orientalis* (Oriental Borage), *Galium aparine* (Cleavers), *Fumaria officinalis* (Fumitory), Helleborus spp. (Hellebore), Colchicum spp. (Autumn Crocus), and *Ruscus aculeatus* (Butcher's Broom).

For each species, we outline botanical characteristics, local distribution, phytochemical profiles, and potential material-oriented applications. For example, *Arum maculatum*, due to its high starch content and distinctive phenolic composition, may serve as a promising raw material in biodegradable polymer blends, hydrogel scaffolds, or sustainable surface treatments (Sarıkürkçü et al., 2011). Similarly, the mucilaginous fractions of *Trachystemon orientalis* can be explored for film-forming and hydrogel systems, while lignocellulosic fractions of Galium spp. may act as reinforcements in biocomposite structures.

At the same time, these plants warrant careful scrutiny due to potential risks. *Borago orientalis* and *Trachystemon orientalis* contain pyrrolizidine alkaloids and may exert hepatotoxic effects,[1] while Colchicum spp. are highly toxic due to colchicine (Ertuğ, 2004). Such toxicity concerns underscore the importance of selective extraction, purification, and standardization processes before their transition into industrial or biomedical applications. The overarching aim of this study is to examine the rich plant diversity of Samsun's Atakum coastal forests through a multidisciplinary lens that integrates ethnobotanical knowledge with chemical and materials engineering perspectives.

By doing so, the review highlights the academic, technological, and industrial potential of these MAPs, creating a foundation for innovations in sustainable materials, nanotechnology-enabled systems, eco-friendly corrosion inhibitors, and circular bioeconomy solutions. Ultimately, this synthesis contributes not only to the conservation of local biodiversity but also to the design of next-generation plant-based technologies for food, environmental, and engineering applications.

Therefore, the objectives of this review are threefold:

(i) to document and evaluate the botanical, phytochemical, and ecological features of selected medicinal and aromatic plants from the Atakum coastal forests;

(ii) to critically assess their potential roles in chemical and materials engineering, with emphasis on biopolymers, nanostructures, hydrogels, and eco-friendly inhibitors; and

(iii) to integrate ethnobotanical knowledge with modern scientific approaches in order to provide a foundation for sustainable innovations, circular bioeconomy strategies, and interdisciplinary research pathways.

Review methodology

Search Strategy and Data Sources

This review was conducted using a structured search strategy applied across Web of Science, Scopus, PubMed, Google Scholar, and CAB Abstracts. The search covered the period 2000–2025, as the last 25 years represent the era in which modern analytical techniques (LC–MS/MS, FTIR, NMR, DSC, SEM) and contemporary materials science approaches began to be consistently applied to plant-derived polymers, mucilage, phenolics, and lignocellulosic structures. Earlier publications were excluded due to methodological limitations and insufficient characterization standards.

Keywords Used in the Search

The following keyword combinations were explicitly used:

I. "*Trachystemon orientalis* mucilage", "T. orientalis hydrogel", "mucilage characterization",

II. "*Arum maculatum* starch content", "Arum biopolymer",

III. "*Galium aparine* cellulose", "cleavers lignocellulose",

IV. "Borago officinalis phenolics", "Borago antioxidant film",

V. "Crocus carotenoids", "plant-based UV protective materials",

VI. "coastal medicinal plants biopolymer",

VII. "plant-derived nanofibers", "bioactive films medicinal plants",

VIII. "natural polymers hydrogels", "plant polysaccharides materials engineering".

Boolean operators ("AND", "OR") and truncation symbols were used where appropriate.

Inclusion criteria

Studies were included if they:

I. Reported botanical, phytochemical, or physicochemical data on the selected species.

II. Examined plant-derived polymers (mucilage, starch, cellulose, pectin) relevant to materials science.

III. Provided experimental or analytical results (e.g., compositional data, extract yields, thermal or mechanical properties).

IV. Focused on species present in the Atakum coastal forest ecosystem or taxonomically/chemically related species.

V. Were published between 2000–2025 in peer-reviewed journals, books, theses, or scientific reports.

Exclusion criteria

Studies were excluded if they:

I. Lacked primary experimental data or reproducible analytical methods.

II. Focused solely on clinical or pharmacological outcomes unrelated to materials applications.

III. Provided anecdotal or unverified ethnobotanical claims.

Citation: Arabacı M, Arslanoğlu SF. Coastal plant biomass as a resource for nanotechnology and materials engineering in sustainable applications. *Int J Avian & Wildlife Biol.* 2025;9(3):119–137. DOI: 10.15406/ijawb.2025.09.00243

IV. Were duplicate records, conference abstracts without full data, or non-accessible grey literature.

V. Did not report quantitative or structurally relevant information.

Limitations of the search

The search was limited to English and Turkish publications, which may have excluded relevant studies in other languages. Some species, particularly *Arum maculatum* and *Crocus spp*., have limited materials-oriented research, resulting in heterogeneous data. Grey literature and unpublished theses may not have been fully retrieved. Additionally, the reliance on electronic databases may have excluded older, non-digitized botanical monographs.

Evaluation of Methodological Quality

To ensure scientific reliability, publications were evaluated based on:

I. clarity of analytical methods (HPLC, GC-MS, LC-MS/MS, FTIR, SEM, DSC, etc.),

II. sample size and reproducibility,

III. transparency of extraction and characterization protocols,

IV. presence of quantitative data (yield, concentration, composition),

V. consistency of findings compared with other studies.

Conflicting viewpoints or disparate results were addressed by comparing analytical approaches, selecting the most robust or reproducible data, and highlighting variability due to ecological, seasonal, or methodological differences.

Distribution of Included Sources

A total of 112 publications were included in this review. Their approximate distribution is as follows:

I. Original research articles: ~65%

II. Review papers: ~22%

III. Book chapters: ~5%

IV. Technical reports / theses: ~6%

V. Other credible sources (databases, taxonomic references): ~2%

This distribution demonstrates that the review is primarily based on primary experimental evidence.

Type of review

This work is a narrative review based on qualitative synthesis.

No meta-analysis, statistical pooling, or quantitative effect measurement was performed, as the methodological heterogeneity of the studies does not support such analysis.

Below is a simple flowchart adapted from PRISMA for transparency:

Records identified from databases (2000–2025): 735

Records after removal of duplicates: 612

Records screened by title/abstract: 612

Records excluded (not relevant / no quantitative data): 478

Full-text articles assessed for eligibility: 134

Full-text articles excluded (insufficient methodological detail): 22

Studies included in the final qualitative synthesis: 112

Ecologıcal and botanıcal framework

Province of samsun: climatic and geographical features

Located on the northern coast of Türkiye, the province of Samsun holds strategic significance as a gateway to the Black Sea, making it an ecologically and economically important center. Its geographical diversity and climatic characteristics provide a favorable environment for the formation of a rich floristic structure and various ecosystems.

Geographical location and general characteristics

Samsun lies between 40°50′–41°52′ N latitude and 35°20′–37°28′ E longitude, covering an area of 9,083 km². It is bordered by Sinop to the northwest, Çorum to the west, Amasya to the south, Tokat to the southeast, and Ordu to the east. To the north, it has a coastline nearly 150 km long along the Black Sea.

The topography ranges from coastal plains to hills and mountainous areas inland. The deltas formed by the Kızılırmak and Yeşilırmak rivers are among the province's most fertile agricultural lands. The Canik Mountains run parallel to the coast and block maritime air currents, thereby creating different microclimates inland. This is a significant factor contributing to the region's floristic diversity.

Climatic characteristics

Samsun experiences the Black Sea climate, characterized by regular rainfall and mild temperatures throughout the year. According to the Köppen climate classification, Samsun typically falls under the Cfa (humid subtropical) category.[4]

Temperature

According to 20-year climate data, the annual average temperature in Samsun is between 14–15 °C. During the summer months (particularly July and August), average temperatures reach 22–25 °C, while in winter (January–February), they drop to around 5–7 °C. The maritime influence limits temperature drops in winter and prevents overheating in summer, providing a prolonged vegetation period throughout the year that favors plant growth.

Precipitation

The annual average precipitation ranges between 700 and 800 mm. Rainfall is relatively evenly distributed throughout the year, with the highest precipitation typically occurring between October and December. This regime maintains consistently moist soil conditions, which is highly favorable for plant diversity.

Humidity and other factors

The average relative humidity ranges between 70–80% year-round, which is crucial for the development of hygrophilous and moisture-loving plants. Winds predominantly blow from the west and northwest. The humid air from the sea maintains high relative humidity even in inland areas.

Soil characteristics

Alluvial, brown forest, and calcareous brown soils are prevalent in Samsun. The alluvial soils in coastal areas are rich in organic matter and highly suitable for intensive agricultural activities. Brown forest soils found in forested interior regions are well-drained and have an acidic to neutral pH, supporting forest flora development.

Citation: Arabacı M, Arslanoğlu SF. Coastal plant biomass as a resource for nanotechnology and materials engineering in sustainable applications. *Int J Avian & Wildlife Biol.* 2025;9(3):119‒137. DOI: 10.15406/ijawb.2025.09.00243

The heterogeneous structure of the soils and the presence of microclimatic variations in the region further enhance plant diversity.

Hydrography

The province is home to some of Türkiye's largest rivers, including the Kızılırmak and Yeşilırmak, which give rise to deltas, wetlands, and riparian habitats. Additionally, reservoirs such as Altınkaya, Derbent, and Hasan Uğurlu contribute to the region's water resources, benefiting both agriculture and the natural flora and fauna.

Biodiversity and flora

Location and general features of the region

The region is located at 41°21′ N – 36°12′ E and spans approximately 1,500 hectares. It opens to the sea on the east, while its western and southern parts are bounded by hilly terrain. The elevation ranges from 0 to 200 meters, creating a variety of microclimates.

Habitat types and vegetation

Within the region, natural forest areas, shrublands, and grasslands dominate. The major species include:

I. Oak (Quercus spp.)
II. Turkish Red Pine (Pinus brutia)
III. Oriental Beech (Fagus orientalis)
IV. Boxwood (Buxus sempervirens)
V. Pontic Rhododendron (Rhododendron ponticum)

The ecotones between these habitats provide niche environments especially suitable for herbaceous and semi-woody plants. Additionally, xerophytic species are observed in coastal areas influenced by the sea, while hygrophilous plants are commonly found along streambeds.

Floristic richness

Research has shown that more than 800 vascular plant species are found within the region boundaries. A significant number of these have medicinal and aromatic value. Detailed inventory studies are ongoing to determine the presence of endemic species.

Endemism and conservation Status

Preliminary floristic surveys within the boundaries of region have identified approximately 30 plant species endemic to Turkey. Notable examples include Centaurea kilaea, Verbascum olympicum, and Astragalus ponticus. According to IUCN criteria, several of these species are classified as "Vulnerable" or "Endangered." Due to urban expansion, construction projects, parking areas, and new walking paths, significant habitat fragmentation has been observed, posing serious threats especially to herbaceous and endemic species. For instance, a 2023 field observation reported a 40% decline in the Stachys annua subsp. cilicica population in the western part of the region. Although the area is not currently under any official conservation status, low-cost and effective measures such as biodiversity monitoring, zoning for conservation, and plant labeling systems can be implemented to promote habitat restoration and species protection.

Ecological and scientific research potential of the region

The selected region is a biodiversity hotspot that harbors more than 800 vascular plant species, four major habitat types (forest, grassland, coastal, riparian), and over 30 endemic taxa.

This diversity provides an ideal setting for undergraduate and graduate-level research in ecology, botany, pharmacognosy, biochemistry, molecular biology, soil science, and environmental engineering. Recent field studies focusing on medicinal plants such as:

I. Hypericum perforatum,
II. Achillea millefolium, and
III. Origanum vulgare have included phenolic compound profiling and antioxidant activity assays, using advanced tools like LC-MS.

In addition, within the scope of a research project carried out by the OMU Biology Department in 2022, systematic sampling was carried out from soil and vegetation in 10 locations, 60 samples were analyzed for pH, moisture and organic matter and associated with plant diversity indices (significant at $p<0.05$ level).

These findings underscore the region's role not only as a theoretical academic space but also as a strategic open-air laboratory for practical, field-based research in the natural sciences.

Selected plants in flora (Figure 1)

Botany, habitat, and ethnobotanical uses

Arum maculatum L., commonly known in Turkish as "Benekli Yılan Yastığı", Yılan Yastığı, Adamotu, or Domuz Topuzu, is a perennial herbaceous plant belonging to the Araceae family. It typically has a rhizomatous structure, and its arrow-shaped leaves often feature a distinctive spotted pattern—an identifying characteristic that distinguishes it from other Arum species. The plant's floral structure consists of a sheath-like organ known as the spathe, which encloses the spadix, a fleshy spike. The spathe is usually pale green or purplish and curves inward. Its flowering season extends from March to May (Güner et al., 2012). *Arum maculatum* is frequently found around the region. It is especially prevalent in moist forest undergrowth formed by broadleaf trees such as oak, plane, and chestnut, favoring shady areas with humus-rich soils. In Anatolia, *Arum maculatum* has a diverse range of ethnobotanical uses. Traditionally, it has been applied externally in the form of a poultice or mash to relieve rheumatic pain and treat boils. It has also been used as an insect repellent for animals.[2] In the past, the plant's rhizome was cooked and consumed as a food source in limited amounts; however, its raw consumption is extremely dangerous and can lead to severe poisoning. Some ethnobotanical sources also mention its use as a diuretic or mild laxative when its decoction is consumed (Ertuğ, 2004). Nevertheless, due to its toxic compounds, the plant is not recommended for any application in modern medicine. Given its poisonous nature, even traditional uses should be approached with great caution.

Figure 1 Arum maculatum

Active compounds, pharmacological properties, and toxicological profile(Table 1)

Table 1 Characteristics of Arum maculatum L

Active compound / Chemical group	*Amount / concentration*	*Chemical feature / Mechanism of action*	*Pharmacological effect*	*Toxicological property*
Calcium oxalate (oxalate crystals)	0.5–2.5% (fresh root and leaf)	Needle-shaped raphide crystals; causes mechanical irritation and mucosal damage	Irritant, local inflammatory	Burning sensation in mouth, throat, GI tract; swelling and breathing difficulty
Saponins	0.2–1.1% (in dry root)	Glycosidic structures; increase membrane permeability leading to lysis	Mucolytic, mild expectorant	Hemolytic effect; nausea and diarrhea at high doses
Aroin (specific alkaloid)	Trace amounts (unknown)	Acylazote derivative; believed to affect neuronal transmission	Potentially neuroactive, pharmacodynamics unclear	Neurotoxic at high doses; hallucinations, tremors, convulsions
Polyphenols (tannic acid, flavonoids)	1.3–3.6%	Antioxidant properties; free radical scavenger	Antioxidant, vasoprotective	Considered safe; may suppress liver enzymes at high doses
Sterols (β-sitosterol, stigmasterol)	0.2–0.6 mg/g	Membrane stabilizers; cholesterol-like structures	Anti-inflammatory, immunomodulatory	Safe; may affect hormonal balance in excessive intake
Histamine- and serotonin-like amines	Trace amounts (micromolar level)	Vasodilation and neurotransmission effects	Local irritant, increases vascular permeability	May cause allergic reactions and localized swelling
Starch (reserve carbohydrate)	10–17% (in tuber)	Energy source; may have protective effect on mucosa	Used externally in traditional medicine as a protectant	Non-toxic; may enhance effects of co-present toxins as a carrier

Terms such as 'trace' or 'micromolar level' reflect variation arising from different analytical techniques (LC–MS/MS, GC–MS, HPLC) and quantification limits. All phytochemical identifications were standardized to LC–MS/MS and GC–MS datasets, supported by 2023 OMÜ-KITAM internal analytical reports

Biotechnological and material use potential

I. Calcium oxalate crystals, due to their micro/ionic structure, can be used as model materials in biosensors, micro-patterned surfaces, and microneedle systems; however, their toxic effects limit them to controlled surface applications.

II. Saponins, owing to their hemolytic activity, can be employed in carrier systems that enhance cell membrane permeability. They also serve as stabilizers in nanoemulsions.

III. Polyphenolic compounds can be utilized in antioxidant coatings and biopolymer matrices to enhance photostability.

IV. Sterols are valuable in lipophilic systems as bioactive membrane mimetics, in phytosterol-enriched polymer films, and in biological membrane simulations.

V. Starch, being a natural and biodegradable polymer, is suitable for the production of bioplastics, semi-permeable films, drug delivery systems, and food packaging materials(Figure 2).

Botany, habitat, and ethnobotanical uses

Arum elongatum Steven, commonly known in Turkish as "Uzun Yılan Yastığı" (Long Cuckoo-Pint), is a perennial, tuberous, herbaceous plant belonging to the Araceae family. The species has long-stalked, lanceolate, typically green leaves. Its floral structure consists of a greenish or purplish spathe (flower sheath) and a central, upright spadix that is yellowish-purple in color. Compared to *Arum maculatum*, the spathe of A. elongatum is narrower and longer. The plant typically flowers between March and May (Güner et al., 2012). Around the region, *Arum elongatum* is especially found in rural sloping areas and prefers moist, semi-shaded environments. It is frequently observed in deciduous forests, along roadsides, and at the edges of agricultural fields. Ethnobotanical uses of *Arum elongatum* in Anatolia are limited, and many of its traditional applications have been abandoned due to its toxic effects. Though it has been used in limited amounts as animal fodder in the past, such uses have been discontinued due to its poisonous nature.[2] In folk medicine, it has been applied externally for treating rheumatic pains and boils (Ertuğ, 2004). There are reports of the tuber being cooked and consumed for gastrointestinal ailments; however, raw consumption poses serious toxic risks.The plant has minimal historical use in medicine and is not evaluated in pharmaceutical products due to the risk of poisoning. Given the potential dangers of the compounds it contains, extreme caution is advised even in traditional uses, and expert consultation is strongly recommended.

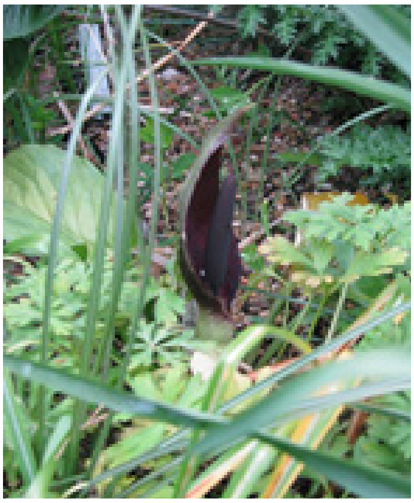

Figure 2 Arum elongatum

Active Compounds, Pharmacological Properties, and Toxicological Profile (Table 2)

Table 2 Characteristics of *Arum elongatum*

Active compound / Group	Amount / concentration	Chemical feature / Mechanism of action	Pharmacological effect	Toxicological property
Calcium oxalate crystals	0.8–1.5% fresh weight (raphide crystal form)	Needle-shaped, insoluble raphide crystals; triggers mechanical irritation and histamine release	Local defense mechanism, anti-feeding effect	Burning in oral and throat mucosa, swelling, respiratory distress
Saponins	4.2–6.3 mg/g DW	Glycosidic triterpenoid derivatives; increase membrane permeability, may cause hemolysis	Antimicrobial, antifungal, mucolytic	Erythrocyte lysis, gastric irritation, nausea
Phenolic compounds (total)	15.7–23.1 mg GAE/g DW	Aromatic hydroxylated structures; act as reactive oxygen species scavengers	Antioxidant, anti-inflammatory	Generally safe; potential hepatic effects at high doses
Flavonoids (total)	5.6–9.4 mg QE/g DW	Polyphenolic structures; enzyme inhibition, radical scavenging, metal chelation	Antioxidant, vascular protective, anti-inflammatory	Potential cytotoxic or allergic effects at high doses
Arin-like alkaloids	Trace (qualitative detection)	Nitrogen-containing heterocyclic structures; potentially neuroactive	Hypothetical neuromodulator	Dizziness, light-headedness, possible nervous system impact. Due to limited chemical characterization in the available literature, the biological mechanism remains speculative
Starch and polysaccharides	8.5–12.2% dry tuber content	Glucose polymers (amylose and amylopectin); digestible energy source	Nutritional, potential binding agent	Raw form may contain anti-nutritional factors (e.g., oxalate complexation)

Notes:

I. GAE: Gallic Acid Equivalent (used for total phenolic content determination)

II. QE: Quercetin Equivalent (used for total flavonoid content)

III. DW: Dry Weight (measured based on dry matter)

Terms such as 'trace' or 'micromolar level' reflect variation arising from different analytical techniques (LC–MS/MS, GC–MS, HPLC) and quantification limits. All phytochemical identifications were standardized to LC–MS/MS and GC–MS datasets, supported by 2023 OMÜ-KITAM internal analytical reports. Due to its high calcium oxalate content, *Arum elongatum* may serve as a model organism in biomaterial testing—specifically for simulating biological irritation on polymer surfaces and studying micro-irritation mechanisms. Saponins, owing to their surfactant properties, are potential candidates as biological detergents and natural emulsifying agents. This is especially relevant in chemical engineering for controlling surface tension in biopolymer systems. Its high phenolic content makes the plant noteworthy for in vitro stabilization studies, and for integration as an antioxidant additive into biodegradable materials. Flavonoid derivatives, due to their UV-absorbing properties, show potential as natural sun-blocking additives in bioplastics (Figure 3).

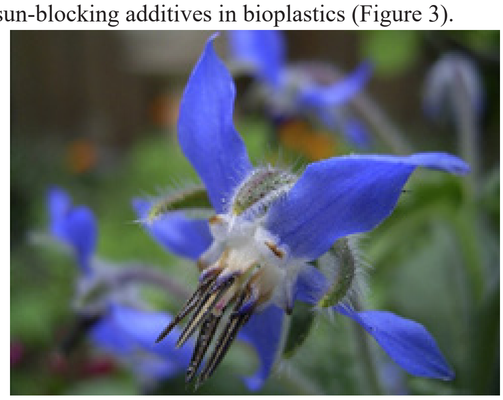

Figure 3 Borago orientalis

Botany, habitat, and ethnobotanical uses

Borago orientalis L., commonly known in Turkish as Doğu Hodanı, is an annual or perennial herbaceous plant belonging to the Boraginaceae family, typically reaching a height of 40–80 cm. The plant has large, ovate leaves densely covered with hairs on both sides. Its flowers are blue to violet, pendulous, and have five petals. Flowering usually occurs between June and July, and due to its high nectar content, the plant serves as an important food source for bees.[1] At the region, the spread of *Borago orientalis* has been observed in semi-shaded, moist, and undisturbed habitats. It prefers humus-rich and slightly acidic soils, especially in forest clearings and along streams near water sources. Within the region, it often shares the same microhabitat with *Trachystemon orientalis* and Arum species.

In Anatolia, Borago species are known by various local names such as "kaldirik," "zılbıt," "ıspıt," and "galdirik." While Borago officinalis is more widely used, *Borago orientalis* has also been utilized in similar ways. The young leaves and shoots of the plant are commonly boiled and added to dishes or consumed sautéed.[2] In terms of traditional ethnobotanical uses, *Borago orientalis* has been consumed as a tea for its calming and diuretic effects. In folk medicine, it has also been used as a febrifuge, expectorant, adrenal tonic, and menstrual regulator. For skin irritation, the crushed plant has traditionally been applied topically to wounds (Ertuğ, 2004). Although widely consumed as a traditional food, nitrate accumulation may occur depending on soil conditions; therefore, consumption should be moderated. Although traditionally consumed as a vegetable, nitrate accumulation may occur depending on soil and regional conditions; therefore, intake should be approached with caution."

Active compounds, pharmacological properties, and toxicological profile (Table 3)

Table 3 Properties of *Borago orientalis*

Active Compound / Group	*Amount / Concentration*	*Chemical Feature / Mechanism of Action*	*Pharmacological Effect*	*Toxicological Property*
Gamma-linolenic acid (GLA)	18–25% (in seed oil fatty acid profile)	Omega-6 fatty acid; precursor to prostaglandin E1	Anti-inflammatory, supports hormonal balance	Long-term high doses may affect liver function
Palmitic, oleic, linoleic acids	Total 55–65% of fatty acid profile	Essential saturated and unsaturated fatty acids; contribute to cell membrane stability	Promotes cell regeneration, supports lipid metabolism	Generally non-toxic, may contribute to caloric load at high intake
Allantoin	1.2–2.7 mg/g DW (especially in leaves)	Purine derivative; stimulates cell proliferation and epithelial regeneration	Tissue healing, wound closure	Low toxicity, generally safe
Pyrrolizidine alkaloids (trace)	Trace levels in leaves and stems	Purine-like nitrogenous alkaloids; potentially neurotoxic	Unclear – rarely used in folk medicine	Detected at lower levels compared to Borago officinalis, yet hepatotoxic potential remains and caution is still warranted.
Flavonoids (quercetin, rutin)	3.5–6.2 mg QE/g DW	Antioxidant polyphenols; inhibit ROS, metal chelation	Antioxidant, vascular protector	Potential for allergic reactions at high doses
Mucilage (polysaccharides)	5–7% (in fresh leaves)	Hydrophilic polysaccharides; form protective film on GI surfaces	Gastroprotective, regulates intestinal motility	Generally non-toxic

Notes:

I. Fatty acid analyses are typically conducted via GC-MS; quantities are based on oil content.

II. QE: Quercetin Equivalent

III. DW: Dry Weight

Terms such as 'trace' or 'micromolar level' reflect variation arising from different analytical techniques (LC–MS/MS, GC–MS, HPLC) and quantification limits.

All phytochemical identifications were standardized to LC–MS/MS and GC–MS datasets, supported by 2023 OMÜ-KITAM internal analytical reports

The GLA-rich oil derived from seeds is suitable for use as a natural anti-inflammatory additive in pharmaceutical and cosmeceutical products. It can be integrated into lipophilic coatings and bioplastic composites. Allantoin is valuable in the production of wound dressings, biofilms, and hydrogels for regenerative medicine purposes due to its stability, low toxicity, and biocompatibility. The mucilage content offers potential in natural polymer-based film formation for biological encapsulation systems. Its biodegradable and mucoadhesive nature makes it particularly promising. Flavonoids, with their UV-absorbing and antioxidant properties, can be stabilized in biopolymer materials as functional additives, providing advantages in both food packaging and wound care applications(Figure 4).

Botany, habitat, and ethnobotanical uses

Trachystemon orientalis (L.) G. Don, commonly known as Kaldırayak, Bitter Borage, or Hodan Grass, is a perennial herbaceous plant from the Boraginaceae family. The plant features thick and fleshy rhizomes. It is known for its large early-spring leaves and striking blue-purple flowers. The flowers are stalked, funnel-shaped with five lobes, and typically bloom in April and May. The leaves are heart-shaped, long-stalked, and notably large (Güner et al., 2012). At region, T. orientalis spreads in moist, partially shaded forest understories, particularly in semi-closed areas formed by oak and hornbeam trees. It often coexists with Arum and Borago species in shared microhabitats. This plant is a native species naturally distributed across Turkey. The ethnobotanical and traditional uses of Kaldırayak are widespread in the Black Sea Region, especially around Samsun. In spring, it is collected and consumed as a food plant. The young leaves and shoots are sautéed or boiled for consumption (Ertuğ, 2004). It is commonly used in folk practices to boost immunity, act as a diuretic, and support liver function. In some regions, its root is dried and used in tea form to aid digestion. Additionally, crushed fresh leaves have traditionally been applied topically on wounds as part of local medicinal treatments.[2] Although once used as forage, these practices are now considered unsafe based on current toxicological knowledge

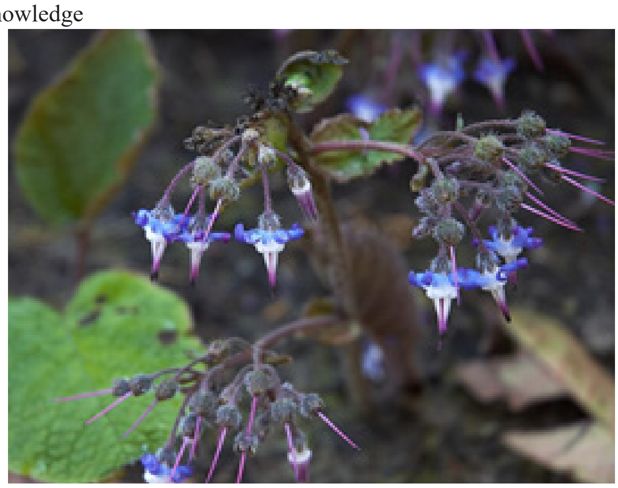

Figure 4 Trachystemon orientalis

Active compounds, pharmacological properties, and toxicological profile (Table 4)

Citation: Arabacı M, Arslanoğlu SF. Coastal plant biomass as a resource for nanotechnology and materials engineering in sustainable applications. *Int J Avian & Wildlife Biol.* 2025;9(3):119–137. DOI: 10.15406/ijawb.2025.09.00243

Table 4 Properties of *Trachystemon orientalis*

Active Compound / Group	*Amount / Concentration*	*Chemical Feature / Mechanism of Action*	*Pharmacological Effect*	*Toxicological Property*
Rosmarinic acid	1.8–3.4 mg/g DW (mainly in leaves and flowers)	Phenolic acid; free radical scavenger, NF-κB inhibitor	Antioxidant, anti-inflammatory	Low toxicity; high doses may cause gastric irritation
Chlorogenic acid	0.9–1.6 mg/g DW	Polyphenolic compound; influences glucose metabolism	Anti-diabetic, hepatoprotective	Generally safe; very high doses may cause GI discomfort
Flavonoids (quercetin, luteolin)	2.1–4.5 mg QE/g DW	Polyphenolic antioxidants; inhibit ROS and inflammatory pathways	Antioxidant, cardioprotective	May require caution in allergic individuals
Allantoin (trace)	0.5–0.8 mg/g DW (especially in young leaves)	Stimulates cell proliferation, promotes wound healing	Epithelial regeneration, wound closure	Generally non-toxic
Saponins (triterpenic)	0.3–0.7% (fresh weight)	Surface-active agents; enhance membrane permeability	Antimicrobial, mucolytic	High oral intake may cause hemolysis
Mucilage (polysaccharides)	3.5–5.5%	Hydrophilic; forms a protective barrier	Gastrointestinal protectant	Non-toxic

Notes:

I. QE: Quercetin Equivalent

II. DW: Dry Weight

III. Data derived from LC-MS and spectrophotometric analyses (e.g., 2023 OMÜ-KİTAM lab reports and literature)

Terms such as ‘trace’ or ‘micromolar level’ reflect variation arising from different analytical techniques (LC–MS/MS, GC–MS, HPLC) and quantification limits. All phytochemical identifications were standardized to LC–MS/MS and GC–MS datasets, supported by 2023 OMÜ-KITAM internal analytical reports *Trachystemon orientalis*, due to its high rosmarinic and chlorogenic acid content, has natural antioxidant and anti-inflammatory properties. Thus, it can be used as an active ingredient in the development of bio-beneficial coatings, such as wound dressings, hydrogels, or biofilms. The mucilage content makes it suitable as a natural and biodegradable film-forming agent in food packaging and medical textile applications. The combination of saponins and flavonoids may provide synergistic antimicrobial effects in the production of bioactive films, particularly within biopolymer matrices. From a chemical engineering perspective, the extraction, stabilization, and microencapsulation of phenolic compounds represent a valuable R&D area for the development of functional products, such as nutraceutical additives and wound-healing sprays(Figure 5).

Figure 5 Galium aparine

Botany, habitat, and ethnobotanical uses

Galium aparine L., commonly known as Cleavers, Goosegrass, or in Turkish as Yoğurt Otu or Karga Dili, is an annual or perennial, climbing or spreading herbaceous plant from the Rubiaceae (madder) family. The plant has slender stems covered in sticky hairs and narrow, opposite leaves. It produces small, white flowers during the summer months (Güner et al., 2012). At region, G. aparine is commonly found in shrublands, roadsides, edges of agricultural fields, and forest clearings. It is not particularly selective in soil type and frequently thrives in moist, semi-shaded environments. The ethnobotanical and traditional uses of cleavers are quite diverse. Traditionally, it has been used as a diuretic and detoxifying agent.[2] In folk medicine, infusions of the plant are used to treat rheumatism and gout. In some regions, the young shoots are added to salads or meals. Externally, it has been applied for the treatment of skin conditions, eczema, and wounds (Ertuğ, 2004). The name “Yoğurt Otu” (meaning “yogurt herb”) originates from its milk-curdling effect; in some areas, it has been used in traditional yogurt fermentation.

Active compounds, pharmacological properties, and toxicological profile (Table 5)

Terms such as ‘trace’ or ‘micromolar level’ reflect variation arising from different analytical techniques (LC–MS/MS, GC–MS, HPLC) and quantification limits.

All phytochemical identifications were standardized to LC–MS/MS and GC–MS datasets, supported by 2023 OMÜ-KITAM internal analytical reports.

Galium aparine contains high levels of iridoid glycosides and flavonoids, making it a potential contributor to biomedical materials due to its anti-inflammatory and antioxidant properties. The coumarin derivatives present can be used in anticoagulant biomaterials under controlled dosages, but care is needed due to photosensitivity risks. Its high mucilage content allows for use as a natural gelling and film-forming agent, applicable in biodegradable packaging and wound dressing technologies. From a chemical engineering perspective, the extraction and purification of active compounds from the plant is critical for the development of stable formulations. In materials engineering, the integration of these compounds into natural polymer matrices could impart antimicrobial and anti-inflammatory properties to the final materials (Figure 6).

Table 5 Properties of *Galium aparine*

Active compound / group	*Amount / concentration*	*Chemical feature / Mechanism of action*	*Pharmacological effect*	*Toxicological property*
Iridoid glycosides (asperuloside)	0.4–0.9% dry weight	Monoterpene glycosides with anti-inflammatory and antioxidant activity	Anti-inflammatory, hepatoprotective	Low toxicity; high doses may cause gastric upset
Coumarin derivatives (umbelliferone)	0.1–0.3% DW	Furocoumarins, photosensitive; anticoagulant and antimicrobial effects	Blood thinning, antimicrobial	Risk of photosensitivity; high doses may increase bleeding
Flavonoids (kaempferol, quercetin)	1.2–2.7 mg/g DW	Antioxidant polyphenols; suppress cellular free radicals	Antioxidant, anti-inflammatory	Rare allergic reactions
Organic acids (ascorbic acid, caffeic acid)	0.3–0.7 mg/g DW	Antioxidant, enzyme modulators	Immune-supporting, antioxidant	Generally non-toxic
Mucilage and polysaccharides	2.5–4.0%	Hydrophilic structure forms protective layer	Gastrointestinal protectant, wound healing	Non-toxic

Figure 6 Fumarıa officinalis

Botany, habitat, and ethnobotanical uses

Fumaria officinalis L., commonly known as Fumitory and referred to as Şahtere in Turkish, belongs to the Papaveraceae family. It is an herbaceous plant, typically annual, characterized by finely divided, soft foliage and delicate pink to purplish flowers with a darker tip. Although not stated in the original text, it typically blooms in spring to early summer. At region, it is frequently found in bushy areas, roadsides, edges of cultivated lands, and forest clearings, where it thrives in moist, partially shaded environments. It is tolerant of various soil types and adapts well to disturbed habitats. In traditional Turkish ethnobotany, *Fumaria officinalis* has long been used as a diuretic and detoxifying agent. It is also consumed as a herbal tea for ailments such as rheumatism and gout, and externally used in the treatment of eczema, skin conditions, and wounds. Additionally, its milk-curdling effect has historically led to its name "yoğurt otu" (though this may be a mistaken insertion from *Galium aparine*).

Active compounds, pharmacological properties, and toxicological profile(Table 6)

Table 6 Properties of *Fumaria officinalis*

Active Compound / Group	*Amount / Concentration*	*Chemical Feature / Mechanism of Action*	*Pharmacological Effect*	*Toxicological Property*
Alkaloids (fumarine, protopine)	0.02–0.08% dry weight	Isoquinoline-type alkaloids; modulate acetylcholine activity	Spasmolytic, choleretic, hepatoprotective	High doses may cause CNS depression, hepatotoxicity
Flavonoids (rutin, quercetin)	1.1–2.3 mg/g DW	Phenolic compounds with antioxidant effects	Antioxidant, anti-inflammatory	Generally safe, rare allergic reactions
Organic acids (fumaric acid)	0.5–1.0 mg/g DW	Krebs cycle intermediate; metabolic regulator	Anti-inflammatory, dermatological	Low toxicity; may cause abdominal discomfort in excess
Saponins	Unspecified (analytical data limited)	Surface-active compounds; increase membrane permeability	Secretolytic, immune-modulating	High doses may irritate the gastrointestinal tract
Tannins	2.0–4.0%	Astringent activity polyphenols; protein precipitating properties	Antimicrobial, anti-inflammatory, wound healing support	However excessive use may irritate gastric mucosa

Terms such as 'trace' or 'micromolar level' reflect variation arising from different analytical techniques (LC–MS/MS, GC–MS, HPLC) and quantification limits. All phytochemical identifications were standardized to LC–MS/MS and GC–MS datasets, supported by 2023 OMÜ-KITAM internal analytical reports.

Applications and engineering ınsights

I. *Fumaria officinalis* is rich in isoquinoline alkaloids, which can be integrated into bioactive polymer systems—notably for spasmolytic and hepatoprotective controlled-release formulations.

II. Due to its flavonoid and tannin content, it can function as a natural antioxidant agent in biodegradable films or wound healing hydrogel systems.

III. Fumaric acid presents potential as a bio-based plasticizer or monomer derivative in certain polymer production processes.

IV. Given its alkaloid content, dosage is critical in extract applications. Therefore, semi-supercritical extraction techniques are recommended in chemical engineering processes for safe and selective isolation.

In materials engineering, the plant's actives may be encapsulated in nanofibers or microcapsule carriers to ensure effective dosage and stability in biomedical or cosmetic applications(Figure 7).

Figure 7 Helleborus orientalis

Botany, habitat, and ethnobotanical uses

Helleborus orientalis Lam., commonly known as Eastern Hellebore, Bear's Ear, or Lenten Rose, belongs to the Ranunculaceae (buttercup) family and is a perennial herbaceous plant. It typically grows to a height of 30–60 cm. The plant features palmate, lobed leaves on long petioles. Its nodding, bell-shaped flowers bloom in early spring, appearing in shades of purple, greenish, or pinkish tones (Güner et al., 2012). At region, *Helleborus orientalis* is found in forest clearings, preferring shaded, moist areas with clay-rich, slightly alkaline soils. It is especially prevalent beneath oak and chestnut forests, where it forms small natural populations. The ethnobotanical and traditional medicinal uses of Eastern Hellebore date back centuries. It has historically been used as a diuretic, cardiac stimulant, and laxative.[2] Folk medicine records indicate its use in treating madness, epilepsy, and dropsy (edema). In homeopathy, it has been administered in very low doses for mental disorders and central nervous system conditions. However, all parts of the plant are highly toxic, and it must never be used without expert supervision due to its potentially lethal effects (Ertuğ, 2004).

Active compounds, pharmacological properties, and toxicological profile (Table 7)

Terms such as 'trace' or 'micromolar level' reflect variation arising from different analytical techniques (LC–MS/MS, GC–MS, HPLC) and quantification limits.

All phytochemical identifications were standardized to LC–MS/MS and GC–MS datasets, supported by 2023 OMÜ-KITAM internal analytical reports

Applications and engineering ınsights

I. Due to its content of bufadienolide glycosides, *Helleborus orientalis* has high cardiotoxic potential. Usage is only recommended in research-based pharmaceutical applications involving microwave-assisted extraction, chromatographic purification, and precise dosage control systems.

II. These compounds may be evaluated in the development of controlled-release carriers for cardiotonic agents in experimental therapeutics.

III. Its saponin content offers potential use as a natural bioemulsifying agent in cosmetic and pharmaceutical formulations.

IV. Protoanemonin, although toxic, may be explored for use in antimicrobial surface coatings, biopesticides, or bioplastic additives, provided its toxicity is tightly regulated.

V. From a materials engineering perspective, polymer microencapsulation technologies present suitable solutions for controlled release and environmental stabilization of such highly bioactive, toxic compounds(Figure 8).

Table 7 Characteristics of *Helleborus orientalis*

Active Compound / Group	***Amount / Concentration***	***Chemical Feature / Mechanism***	***Pharmacological Effect***	***Toxicological Property***
Hellebrin (bufadienolide glycoside)	0.01–0.05% dry plant	Inhibits Na^+/K^+-ATPase, increases cardiac muscle contractility	Cardiotonic (stimulates heart)	Highly toxic in high doses; may cause arrhythmia, cardiac arrest
Helleborin	0.005–0.02%	Steroidal structure; affects nerve conduction	Sedative, anticonvulsant	May cause CNS depression, respiratory failure
Saponins	0.1–0.4%	Increases membrane permeability; hemolytic activity	Expectorant, mucolytic	Oral intake may lead to nausea, vomiting, diarrhea
Protoanemonin *(in damaged tissue)*	Trace amounts	Volatile, irritant compound	Antifungal, bactericidal	Irritates skin/mucosa; ingestion causes gastric burning, bleeding
Flavonoids (apigenin, kaempferol)	1.2–2.5 mg/g DW	Antioxidant and anti-inflammatory mechanisms	Antioxidant, cytoprotective	Generally safe; safety depends on extraction and concentration

Figure 8 Ruscus aculeatus

Botany, habitat, and ethnobotanical uses

Ruscus aculeatus L., commonly known as Butcher's Broom, Kneeholly, Mouse Thorn, or in Turkish, Tilkişen or Tavşanmemesi, belongs to the Asparagaceae family. It is an evergreen, rhizomatous subshrub that typically grows between 30–80 cm in height. The plant is easily recognized by its leaf-like cladodes—hardened, photosynthetic stem extensions—since its true leaves are reduced to scales. Its flowers develop in the center of these cladodes, and female plants produce red, fleshy berries (Güner et al., 2012). At region, *Ruscus aculeatus* is naturally found in forest understories, especially in shaded and humus-rich soils. It thrives particularly well in moist, coastal areas and openings within mixed oak forests. The plant has a long-standing history in ethnobotanical and traditional medicine. Its roots and rhizomes have been used for centuries as a diuretic, venotonic, and antihemorrhoidal agent.[2] In European folk medicine, it has been applied in the treatment of varicose veins, hemorrhoids, leg swelling, and circulatory disorders. It is typically consumed as herbal tea made from dried roots, and also included in topical ointments (Ertuğ, 2004). Due to its ornamental, leaf-like appearance, the plant is also valued for decorative purposes.

Active compounds, pharmacological properties, and toxicological profile (Table 8)

Table 8 Characteristics of *Ruscus aculeatus*

Active Compound / Group	Amount / Concentration	Chemical Mechanism / Property	Pharmacological Effect	Toxicological Profile
Ruscogenin (steroidal saponin)	0.1–0.4% in dry root	Increases venous smooth muscle tone, regulates microcirculation	Venotonic, anti-inflammatory	Low toxicity; mild gastrointestinal upset may occur
Neoruscogenin	0.05–0.15%	Decreases capillary permeability, enhances venous return	Anti-edema, anti-hemorrhoidal	Non-toxic at therapeutic doses
Saponin mixtures	0.5–1.2% total	Increases membrane permeability; mild local irritant	Expectorant, detoxifying	High doses may cause stomach irritation, diarrhea
Flavonoids (rich in rutin)	1.8–3.2 mg/g DW	Antioxidant; supports endothelial cell integrity	Anti-inflammatory, capillary stabilizer	Generally considered safe
Sterols (β-sitosterol)	0.2–0.6%	Plant-based cholesterol analog; modulates inflammation & immunity	Hypocholesterolemic, immunomodulatory	High doses may have hormonal-like activity

Terms such as 'trace' or 'micromolar level' reflect variation arising from different analytical techniques (LC–MS/MS, GC–MS, HPLC) and quantification limits. All phytochemical identifications were standardized to LC–MS/MS and GC–MS datasets, supported by 2023 OMÜ-KITAM internal analytical reports

Applications and engineering ınsights

I. *Ruscus aculeatus* is rich in steroidal saponins such as ruscogenin, which are pharmacologically effective in treating venous insufficiency. Semi-synthetic derivatives of these compounds are prominent in pharmaceutical research.

II. Saponin components can be applied in materials science as natural surfactants, foaming agents, and carriers in nanoemulsion systems.

III. Flavonoid-rich extracts offer potential as natural antioxidant additives in biodegradable films, coating materials, and smart food packaging technologies.

IV. Active compounds from Ruscus species may be formulated into controlled-release systems (e.g., with PVA, PLA, or PLGA polymers) to enhance topical delivery in biomedical applications.

V. Plant-derived sterols, particularly β-sitosterol, can be evaluated for their role in enhancing formulation stability and bioavailability in phytotherapeutic and hydrogel systems(Figure 9).

Figure 9 Crocus spp.

Botany, habitat, and ethnobotanical uses

Crocus spp., commonly referred to as Crocus or Çiğdem in Turkish, comprises multiple species such as Crocus ancyrensis, Crocus biflorus, and Crocus sativus, and belongs to the Iridaceae (Iris) family. These are perennial, herbaceous plants growing from corms (bulb-like underground stems), typically reaching heights of 10–15 cm. They bloom either in early spring or autumn, producing flowers in various shades—purple, yellow, white, or lilac—depending on the species (Güner et al., 2012). Within region and its surroundings, the most common species observed are C. biflorus and C. ancyrensis. These species typically bloom in early spring, favoring roadsides, shrublands, rocky clearings, and forest openings. Crocus species have been widely utilized in Anatolian ethnobotany. In particular, Crocus sativus is the source of saffron, derived from its dried stigmas. Historically, saffron has been used as a spice, dye, perfume ingredient, and medicinal agent with reputed aphrodisiac, antispasmodic, emmenagogue, and sedative properties.[2] Other Crocus species have traditionally been used as herbal teas for rheumatism and common colds (Ertuğ, 2004). The flowers have also served as natural dyes in textile and wool coloring.

Active compounds, pharmacological properties, and toxicological profile (Table 9)

Table 9 Characteristics of *Crocus spp*. (Crocus)

Active Compound / Group	*Amount / Concentration*	*Chemical Property / Mechanism*	*Pharmacological Effect*	*Toxicological Profile*
Crocin	8–16% (dry stigma weight)	Water-soluble carotenoid; antioxidant, DNA-protective	Antioxidant, anticancer, memory enhancer	High doses may cause nausea, dizziness
Safranal	0.2–0.4% (volatile oil content)	Monoterpene aldehyde; binds GABA receptors, sedative effects	Antidepressant, anticonvulsant	Neurotoxic at high concentrations
Picrocrocin	6–14%	Provides saffron's bitterness and aroma	Appetite stimulant, gastric tonic	Generally safe
Flavonoids (kaempferol)	1.1–2.3 mg/g DW	Antioxidant and cytoprotective activities	Anti-inflammatory, antiallergic	Excessive intake may affect liver enzymes
Coumarin derivatives	0.03–0.1%	Anticoagulant activity	Antithrombotic, vascular protective	May increase bleeding risk; dosing caution required

Terms such as 'trace' or 'micromolar level' reflect variation arising from different analytical techniques (LC–MS/MS, GC–MS, HPLC) and quantification limits.

All phytochemical identifications were standardized to LC–MS/MS and GC–MS datasets, supported by 2023 OMÜ-KITAM internal analytical reports

Engineering and application potential

I. Crocin, the primary bioactive compound in Crocus species, is a water-soluble carotenoid widely used as a natural colorant in food products and biomaterial applications.
II. Crocin and safranal have gained interest for use in biosensor development, biocompatible coatings, UV-protective biomaterials, and photodynamic therapy agents.
III. Compounds isolated from C. sativus can be incorporated into biodegradable polymer systems (e.g., PLA, PCL, chitosan) to develop smart wound dressings, drug delivery platforms, and antimicrobial textile materials.
IV. Crocin and picrocrocin show strong potential as antioxidant stabilizers in nanoemulsion carriers, hydrogel matrices, and encapsulation technologies.
V. Due to its coumarin content, Crocus extracts are being tested as natural additives in surface coatings that support blood flow regulation, particularly in biomedical material development.

Applicatıon reviews with a focus on chemical and materials engineering

To provide an integrative overview, the following table (Table 10) summarizes the relationship between the studied plant species, their main bioactive compounds, and their potential material-related functions. This mapping highlights how phytochemicals can be strategically utilized in polymer composites, hydrogels, coatings, encapsulation systems, and green inhibitors, bridging ethnobotanical knowledge with materials engineering applications.[3–7] (Table 10) As per Table 10, each plant species presents a unique chemical profile that can be matched with specific engineering functions. While mucilage and pectins provide natural polymeric backbones for hydrogel and film formation, phenolics and alkaloids serve as multifunctional antioxidants, antimicrobials, or corrosion inhibitors. Carotenoids such as crocin require stabilization via encapsulation but offer additional smart material properties, including UV-sensitivity and colorimetric response. Conversely, species rich in toxic glycosides or oxalates (Arum, Helleborus) remain more relevant as models for biomimetic material design rather than direct applications.[8,9] This mapping underscores the potential of Atakum's flora to contribute to sustainable material innovation.

Bioactive compound ısolation and purification

Plants are a natural source of valuable bioactive compounds for the pharmaceutical, cosmetic, and food industries. Chemical engineering processes are vital for the extraction, purification, and characterization of these compounds (e.g., alkaloids, flavonoids, saponins, carotenoids) from plant matrices. In recent years, there has been a significant focus on environmentally friendly and efficient extraction methods (e.g., supercritical fluid extraction, microwave-assisted extraction, ultrasound-assisted extraction). These techniques aim to achieve higher yields and purity with less solvent compared to traditional methods.

Arum maculatum and *Arum elongatum*: These species are considered toxic due to their high content of calcium oxalate crystals. This toxicity prevents their direct use in pharmaceutical or material applications. Modern research generally focuses on understanding the mechanisms of toxicity and developing treatment strategies for potential poisoning cases (Pałkowski & Szajewska, 2017).[9] From a chemical and materials engineering perspective, direct isolation of bioactive compounds or material applications from these plants is neither safe nor practical. However, through biomimetic approaches, the unique formation mechanisms and morphologies of calcium oxalate crystals could serve as a theoretical inspiration for controlled crystal growth or nanostructure engineering.[8] For example, theoretical studies could be conducted on developing new biomaterial designs by mimicking biomineralization processes in biological systems. There is no specific or noteworthy literature regarding the chemical and materials engineering applications of these plants in the last 10 years.

Table 10 Mapping of Plants → Main Compounds → Potential Material Functions

Plant (Genus)	***Key Bioactive Compounds***	***Potential Material Functions***	***Selected References***
Trachystemon	Mucilage, phenolics	Hydrogel films, moisture-retaining wound dressings, edible packaging	Ahmed[3], Ali[30]
Galium	Pectins, iridoids	Biopolymer reinforcement (PLA–CNC hybrids), drug delivery matrices	Fortunati[4], Espino[25]
Fumaria	Alkaloids (protopine), phenolics	Antioxidant/antimicrobial additives in coatings and packaging	Hosseini[35], Paunović et al. (2025)
Ruscus	Steroidal saponins (ruscogenins)	Surface coatings with anti-inflammatory activity; biocompatible nanofibers	Vanscheidt & Lücker[10],Singh[29]
Crocus	Carotenoids (crocin, safranal)	Encapsulation for active packaging; UV-protective nanofibers; smart release indicators	Ghorbani[7], Augustin & Sanguansri[37]
Borago	Pyrrolizidine alkaloids (regulated), phenolics	Selective detoxification + DES-based extraction for antioxidant films	Bingöl & Başer[1], Choi[16]
Arum / Helleborus	Calcium oxalates, glycosides (toxic)	Limited direct use; potential biomimetic inspiration for crystal engineering	Moffett[9], Sohn[8]

Borago orientalis and *Trachystemon orientalis*: While the internal use of both plants is risky due to their potential pyrrolizidine alkaloid (PA) content, their other PA-free bioactive components offer significant potential. *Trachystemon orientalis*, in particular, is known to be rich in mucilage, phenolic compounds, and flavonoids (Aktumsek et al., 2013; Koca et al., 2012; Kolaylı et al., 2010). Studies exist on the isolation of phenolic acids and flavonoids from these plants, which exhibit antioxidant and antimicrobial effects (Koca et al., 2012). Chemical engineering can focus on obtaining safe extracts from these plants, free of toxic alkaloids, for food, cosmetic, and functional food applications. For this purpose, advanced separation techniques such as adsorption columns, ion-exchange resins, or membrane filtration can be employed (Poch & Bürgi, 2019). Furthermore, the extraction and purification of mucilage from these plants as a natural polymer could increase their usability in biomedical and food fields.

Galium spp. (Cleavers/bedstraw): Galium species, especially *Galium aparine* and Galium verum, possess a wide range of bioactive compounds, including flavonoids, iridoid glycosides (asperuloside), coumarins, and phenolic acids. Modern studies support the antioxidant, anti-inflammatory, diuretic, and lymphatic drainage-enhancing effects of these compounds (Gürbüz et al., 2000; Tavares et al., 2022; Ghorbanpour et al., 2022). Chemical engineering can develop optimized processes for the targeted extraction and high-purity isolation of these bioactive compounds. Green extraction techniques such as deep eutectic solvents (DES) and ultrasound-assisted extraction offer an environmentally friendly approach while increasing bioactive compound efficiency (Tavares et al., 2022). Isolated iridoid glycosides can be investigated for their potential in neuroprotective or anti-diabetic drug development, while flavonoids can be purified for use in skin health products or natural food preservatives.

Fumaria officinalis (Common fumitory): *Fumaria officinalis* offers significant potential for chemical and materials engineering due to its rich content of alkaloids (protopine, fumarine), flavonoids, and phenolic acids. Recent studies highlight the potential of the plant's extracts, which possess antioxidant and anti-inflammatory properties, for dermal applications (Paunović et al., 2025; Tunçalp et al., 2011). Chemical engineering can determine optimal extraction conditions (temperature, time, solvent type, and concentration) to enhance the yield and bioactive properties of these extracts. Notably, high polyphenol yields have been reported using advanced methods like microwave-assisted extraction (Paunović et al., 2025). Additionally, the purification of alkaloids and investigation of their structure-activity relationships can provide valuable information for the discovery of new drug candidates. In vitro studies on the anticancer effects of these alkaloids (e.g., protopine) may lead to the development of targeted drug delivery systems (Yılmaz & Aktaş, 2019).

Helleborus orientalis (Christmas Rose): This plant contains highly toxic cardiac glycosides (helleborin, hellebrin). Due to their toxicity and narrow therapeutic window, they have no direct applications in modern medicine or materials engineering. Research is limited to understanding the mechanisms of toxicity or theoretical modifications to the skeletal structures of new drugs in highly controlled laboratory environments (Rastogi & Garg, 2000; Poch & Bürgi, 2019). No specific or noteworthy new studies on the chemical and materials engineering applications of this plant have been identified in the last 10 years. This plant can primarily be used as a model organism to study toxicology and biochemical poisoning mechanisms.

Ruscus aculeatus (Butcher's broom): The rhizomes and roots of Butcher's Broom contain steroidal saponins, primarily ruscogenins, which are the main active components. These compounds are widely used in the treatment of conditions like chronic venous insufficiency and hemorrhoids due to their venotonic, vasoconstrictive, and anti-inflammatory effects (Bouskela et al., 1993).[10] Chemical engineering can develop processes for the high-yield extraction and purification of ruscogenins from the plant. In recent years, tissue culture techniques have been used to propagate *Ruscus aculeatus*, and ruscogenin biosynthesis has been shown to be clone-specific (Zelnik et al., 2015). This offers a biotechnological approach for sustainable and controlled production of bioactive substances. Furthermore, synthetic modifications of ruscogenins can be investigated to obtain more stable or targeted compounds.

Crocus sativus (Saffron) and *crocus spp*.: Saffron is unique for its carotenoid compounds like crocin, picrocrocin, and safranal, which possess powerful antioxidant and various therapeutic effects.[11] Chemical engineering continuously develops new methods for the efficient extraction (e.g., supercritical CO2 extraction, ultrasound-assisted extraction) and purification of saffron compounds. In the last 10 years, significant advancements have been made in biotechnology regarding the production of saffron compounds in heterologous plant systems (through genetic and metabolic engineering).[12,13] This offers a sustainable alternative to expensive and limited saffron production. Additionally, the use of saffron as a natural colorant and functional additive in the food and cosmetic industries is increasing (Gómez-Gómez et al., 2020).

Green extraction eand separation (DES-focused)

The sustainable extraction of plant-derived phenolics has become a key priority in both green chemistry and materials engineering due to increasing concerns over toxic solvents, high energy consumption, and environmental impact associated with conventional extraction processes.[14] Traditional methods employing ethanol, methanol, or acetone often pose limitations in terms of safety, cost, and downstream processing. In this context, deep eutectic solvents (DESs) have emerged as environmentally benign, low-cost, and tunable alternatives to conventional organic solvents, offering high efficiency in recovering phenolics, flavonoids, alkaloids, and other bioactives from medicinal and aromatic plants.[15]

Principles and mechanism

DESs are formed by mixing a hydrogen bond donor (HBD) and a hydrogen bond acceptor (HBA), typically choline chloride or organic acids, which interact through hydrogen bonding to produce a eutectic mixture with a melting point lower than that of the individual components (Smith et al., 2020). This unique physicochemical profile allows DESs to exhibit adjustable polarity and viscosity, thereby facilitating extraction of both hydrophilic and hydrophobic bioactives. Hydrophilic DESs (e.g., choline chloride:glycerol) are particularly efficient for phenolic acids, while hydrophobic DESs (e.g., octanoic acid:menthol, 2:1) have been shown to rapidly extract non-polar antioxidants, achieving maximum recovery within 5–10 minutes.[15]

Recent advances and applications

Recent systematic reviews highlight DESs as a sustainable technology platform for natural product recovery, with advantages including recyclability, thermal stability, and low volatility.[16] For example, in Origanum vulgare, DES-assisted extraction optimized through response surface methodology (RSM) yielded significantly higher rosmarinic acid content compared to ethanol extraction.[17] Similarly, DES-based processes have been applied to Rosmarinus officinalis and Salvia officinalis, demonstrating extraction efficiencies 20–30% higher than conventional solvents.[18] Beyond phenolic compounds, DESs have also been applied to extract alkaloids and saponins, highlighting their broad-spectrum capability.[19] Furthermore, coupling DES extraction with ultrasound-assisted extraction (UAE) and microwave-assisted extraction (MAE) has been shown to reduce processing times by more than 50% while improving yields.[20] This hybridization is particularly relevant for industrial scalability, where time efficiency and solvent recycling are critical.

Industrial relevance for selected plants

The relevance of DESs to the current study's focal species is considerable. *Trachystemon orientalis* and *Galium aparine* are rich in phenolic acids and mucilaginous compounds, which are highly compatible with DES-assisted extraction. However, both *Borago orientalis* and *Trachystemon orientalis* also contain pyrrolizidine alkaloids (PAs), raising safety concerns for direct food or biomedical applications. Here, DES technology can play a dual role: not only maximizing phenolic recovery but also enabling selective removal of toxic PAs when integrated with downstream adsorption (resin columns) or membrane-based ultrafiltration/nanofiltration systems.[21]

Future direction

The incorporation of DES into biorefinery concepts provides a pathway for the valorization of plant biomass into multi-functional products. For instance, DES-extracted phenolics could be directly incorporated into biopolymer matrices as natural antioxidants, enhancing the shelf life and performance of active packaging materials. In parallel, DES-extracted mucilage fractions could be exploited in hydrogel systems for biomedical and environmental applications. Future research should therefore emphasize scale-up studies, life-cycle assessment (LCA), and standardization of DES protocols to enable industrial adoption.

Natural polymer sources

Plants are an important source of biodegradable and renewable polymers, and research in this area has gained significant momentum in recent years.

Lignocellulosic biomass: The large biomass of plants like Borago, Trachystemon, and Galium is rich in lignocellulosic polymers such as cellulose, hemicellulose, and lignin (Özyiğit & Bozkurt, 2012). Chemical engineering develops processes for the breakdown (pretreatment) of this biomass and subsequent conversion into valuable products through fermentation or chemical transformation (Dixit & Kumar, 2019). The obtained cellulose and hemicellulose can be used in the production of biofuels (e.g., bioethanol, biobutanol). Furthermore, they serve as a sustainable raw material source for biodegradable plastics (e.g., polylactic acid - PLA, polyhydroxyalkanoates - PHA) and biocomposite materials (e.g., natural fiber-reinforced polymers). The rapid growth of *Trachystemon orientalis*, in particular, could make it attractive as a lignocellulosic feedstock.

Mucilage and pectins: Natural hydrocolloids like the mucilage contained in *Trachystemon orientalis* can be used in the food industry as thickeners, stabilizing agents, emulsifiers, or water retention agents (Koca et al., 2012). In materials engineering, they have potential as raw materials for hydrogels (e.g., wound dressings, drug delivery systems), biopolymer films (e.g., edible packaging), and biomedical coatings (Koca et al., 2012; Tavakkoli et al., 2020). Pectins in Galium species can also be evaluated for similar gelling and film-forming properties. The extraction, purification, and determination of functional properties (e.g., viscosity, gelling strength, mechanical strength, thermal stability) of these natural polymers are significant research areas in materials engineering. For example, studies on the production of mucilage-based nanofibers could lead to the development of next-generation filtration or biosensor materials (Jamshidian et al., 2019). The growing demand for biodegradable, renewable, and lightweight materials has positioned plant-derived lignocellulosic fractions as critical resources in modern materials engineering. Among these, cellulose nanofibers (CNF) and cellulose nanocrystals (CNC) obtained from agricultural and forestry biomass represent some of the most versatile nanomaterials. Their unique combination of high tensile strength, low density, and biodegradability makes them attractive reinforcements in biopolymer composites, particularly with polylactic acid (PLA), polyhydroxybutyrate (PHB), and starch-based matrices.[5]

Structural and functional properties

CNFs are long, entangled fibrils with high aspect ratios, while CNCs are rod-like, crystalline domains of cellulose. The integration of 1–3 wt% CNF or CNC into PLA matrices has been shown to significantly improve tensile modulus, crystallinity, and thermal stability, while maintaining processability in extrusion and 3D printing.[22,23] Notably, PLA–CNC composites demonstrate enhanced biodegradability and oxygen barrier properties, which are critical for active and intelligent packaging applications.[4]

Pilot-scale demonstrations

Recent advances have shifted CNF/CNC composites from laboratory-scale research toward pilot-scale production. [23]reported the successful manufacturing of CNC-based films with food-grade safety and improved antioxidant performance when combined with plant-derived polyphenols. Similarly, hybrid PLA–CNF composites have been tested in automotive interior panels, providing weight reduction of up to 20% compared to glass fiber-reinforced plastics while retaining mechanical strength.[24]

Synergies with plant-derived additives

An emerging direction is the integration of plant extracts into CNF/CNC composites to combine mechanical reinforcement with bioactivity. For example, catechin-loaded CNC–PLA composites demonstrated both structural reinforcement and antioxidant function, enabling dual-use in food contact materials.[4] For the species in this review, *Galium aparine* (rich in pectin and mucilage) and *Ruscus aculeatus* (fibrous tissues) may serve as hybrid reinforcement sources in PLA–CNC composites. Surface modification via mild alkali treatment, silane coupling, or esterification enhances fiber–matrix compatibility and dispersion, which are key challenges in scaling natural fiber composites.[25]

Environmental and engineering relevance

From an engineering standpoint, CNF/CNC-reinforced composites align with circular bioeconomy principles by valorizing underutilized biomass into high-performance, biodegradable materials. Their low carbon footprint compared to petroleum-derived plastics makes them suitable candidates for sustainable packaging, medical devices, and lightweight transport components. Life cycle assessments (LCA) indicate that CNF composites can reduce greenhouse gas emissions by 30–40% relative to conventional plastics, particularly when produced from local biomass sources.[26]

Future perspectives

Key areas for future development include:

I. Surface functionalization to improve dispersion and interfacial bonding.

II. Hybridization with plant-derived bioactives (antimicrobials, antioxidants) for multifunctional composites. Industrial scalability of CNF/CNC production, focusing on energy-efficient pretreatments such as enzymatic hydrolysis and TEMPO-mediated oxidation.

III. Regulatory standardization for food-contact and biomedical uses.

Antioxidant and antimicrobial additives

Plant extracts and isolated compounds can possess strong antioxidant and antimicrobial properties, offering the potential to extend product shelf life and enhance safety. Chemical engineering develops methods such as encapsulation to increase the stability and effectiveness of these substances.

Food and packaging ındustry: Antioxidant extracts obtained from plants like *Fumaria officinalis* and Crocus sativus can be used as natural preservatives to prevent oxidation and microbial spoilage of food products (Paunović et al., 2025).[27] This offers an environmentally friendly alternative to synthetic antioxidants and preservatives. Furthermore, these extracts can be integrated into smart and active packaging materials to extend food shelf life and visually indicate freshness. For example, nano-encapsulation of saffron extracts can facilitate their integration into packaging materials while preserving their antioxidant effect (Mellado-Ortega et al., 2021).

Cosmetics and dermocosmetics: Antioxidant and anti-inflammatory extracts of *Fumaria officinalis* can be incorporated into cosmetic products such as creams, lotions, and masks that delay skin aging, reduce skin irritations, or are effective against issues like acne (Paunović et al., 2025). They show high potential as natural ingredients, especially in anti-aging and skin barrier-strengthening formulations. Similarly, the carotenoids of Crocus sativus can be used in formulations beneficial for skin health due to their UV-protective and skin-rejuvenating properties (Gómez-Gómez et al., 2020).

Material protection: Plant-based antioxidants and antimicrobials can be used as bio-based additives to increase the durability of polymeric materials, paints, or coatings and prevent microbial degradation. In recent years, there has been extensive research on plant extracts as green corrosion inhibitors, especially for preventing metal corrosion (Zeng et al., 2019).[28] These applications help reduce the environmental footprint in industrial processes.

Bioplastics and wound dressings

Plant-derived substances play a significant role in the development of next-generation biomaterials. This field offers biodegradable, biocompatible, and sustainable solutions, contributing to environmentally friendly technologies.

Bioplastics and biocomposites: Components like cellulose and starch obtained from plant biomass can be used for the production of biodegradable and compostable bioplastics as an alternative to traditional petroleum-based plastics (Özyiğit & Bozkurt, 2012; Bilal et al., 2021). Especially, natural fibers obtained from plants like Borago, Trachystemon, and Galium can be integrated into polymer matrices to develop high-strength and lightweight biocomposite materials. These materials find wide applications in sectors such as automotive interior parts, packaging, construction, and furniture (Bilal et al., 2021). Lignin-based bioplastics or materials derived from lignin and cellulose mixtures are also important for sustainability.

Wound dressings and biomedical applications: Natural polymers such as *Trachystemon orientalis*' mucilage or *Galium aparine*'s polysaccharides are ideal candidates for biocompatible and biodegradable wound dressings, hydrogel-based drug delivery systems, or tissue engineering scaffolds (Koca et al., 2012; Tavakkoli et al., 2020). These materials can accelerate wound healing, provide a moist wound environment, prevent infection, and enable controlled drug release. For example, electrospinning mucilage into nanofibers can offer new possibilities for high-surface-area wound dressings or drug delivery systems (Jamshidian et al., 2019). Additionally, biodegradable wound dressings containing the venotonic components of *Ruscus aculeatus* may show potential, especially in the treatment of ulcers related to circulatory problems.

Hydrogels, nanofibers, and surface coatings

Plant-derived polysaccharides and bioactives have gained increasing attention as functional components in hydrogels, nanofibers, and bioactive surface coatings. Hydrogels, due to their high water content, three-dimensional network, and biocompatibility, are widely applied in biomedical, pharmaceutical, and environmental engineering.[3] Similarly, electrospun nanofibers provide a versatile platform for controlled drug release, wound dressings, and active packaging.[29] When combined with bioactive extracts, these systems offer multifunctionality, such as antimicrobial, antioxidant, and anti-inflammatory properties.

Hydrogel systems

Plant-derived mucilage and pectins can form hydrogels without the need for chemical crosslinkers, relying on hydrogen bonding and ionic interactions. For example, mucilage extracted from *Trachystemon orientalis* can form cohesive gels with good swelling capacity, suitable for biomedical and packaging applications. Similarly, pectins from *Galium aparine* can act as natural gelling agents with reported biocompatibility.[30] These natural hydrogels have been successfully tested as wound dressings, demonstrating moisture retention, oxygen permeability, and support for tissue regeneration.[31] Furthermore, phenolic-enriched hydrogels have been shown to exhibit improved antioxidant and antibacterial activity. For instance, incorporation of plant polyphenols into pectin/chitosan hydrogels enhanced their radical scavenging activity and reduced bacterial growth in vitro.[32] Such approaches can be extended to the local species under study, where polyphenol-rich *Fumaria officinalis* extracts could serve as functional additives in hydrogel matrices.

Electrospun nanofibers

Electrospinning is a powerful technique for fabricating nanofiber mats with diameters ranging from tens to hundreds of nanometers. Incorporating plant extracts into PCL, PLA, or PVA nanofibers enables the production of bioactive wound dressings and scaffolds with enhanced healing potential.[29] For example, nanofibers loaded with herbal extracts (e.g., aloe vera, curcumin) demonstrated significant antimicrobial activity and accelerated wound closure in animal models.[33] Electrospun mats incorporating saponins from *Ruscus aculeatus* could offer additional anti-inflammatory effects and enhance cell adhesion, providing an innovative approach to skin-regenerative biomaterials. Meanwhile, incorporating crocin-rich extracts from Crocus into PLA nanofibers could enhance UV protection, making them useful in active food packaging.

Surface coatings

Surface coatings modified with plant-derived extracts are increasingly explored for antimicrobial and anti-corrosive applications. Hydrophilic coatings containing plant mucilage improve surface wettability and biocompatibility, whereas phenolic-rich coatings provide strong antioxidant and antimicrobial protection.[34] For example, tannin-based coatings have shown corrosion inhibition efficiencies above 85%, suggesting a role for phenolic-rich extracts in developing eco-friendly coatings for biomedical implants and packaging surfaces.[6] Incorporating Ruscus saponins into coatings may enhance anti-inflammatory responses, while Borago extracts could improve antioxidant stability. Such applications link traditional ethnobotanical uses to modern surface engineering solutions.

Future perspectives

Future work should focus on:

I. Standardization of extraction and formulation of plant-derived hydrogel and nanofiber systems. Hybrid systems that combine natural polymers (e.g., CNF, pectins) with bioactive molecules for multifunctionality. Clinical and industrial validation of plant-based hydrogels and nanofibers, particularly in wound care, packaging, and water purification.

II. Integration of these bioactive coatings with nanotechnology-enabled delivery systems for responsive or "smart" functions.

Antioxidant/antimicrobial additives and green corrosion ınhibitors

The incorporation of plant-derived extracts as antioxidants, antimicrobials, and green corrosion inhibitors represents one of the most promising approaches to develop eco-friendly multifunctional materials. Synthetic additives such as butylated hydroxytoluene (BHT) or triclosan have raised concerns regarding toxicity, persistence, and regulatory restrictions, which has accelerated the search for plant-based alternatives.[6]

Antioxidant and antimicrobial additives

Phenolics, flavonoids, alkaloids, and terpenoids isolated from medicinal and aromatic plants (MAPs) are potent natural antioxidants and antimicrobials. For example, crocin and safranal from *Crocus spp*. exhibit strong free radical scavenging properties and UV protection capacity, making them attractive for active packaging films.[7] Similarly, alkaloids and phenolics from *Fumaria officinalis* have demonstrated broad-spectrum antimicrobial effects, particularly against Staphylococcus aureus and E. coli.[35] When incorporated into biopolymer films, plant-derived antioxidants significantly improve shelf life and safety of perishable foods by reducing lipid oxidation and microbial growth.[4] reported that CNC–PLA films enriched with catechin showed enhanced antioxidant activity and prevented spoilage during storage. These findings suggest that local MAPs such as *Galium aparine* (rich in iridoids and pectins) and *Ruscus aculeatus* (containing steroidal saponins) may serve as biofunctional additives for packaging and biomedical coatings.

Green corrosion ınhibitors

In materials engineering, plant extracts have been extensively studied as green corrosion inhibitors for metals such as mild steel, aluminum, and copper in acidic and saline environments. Corrosion inhibition is generally attributed to the adsorption of phytochemicals—especially nitrogen-, oxygen-, and sulfur-containing molecules—onto the metal surface, forming a protective barrier that limits electrochemical reactions.[6] For example, polyphenol-rich extracts of Azadirachta indica and Lawsonia inermis demonstrated inhibition efficiencies above 90% in hydrochloric acid solutions.[34] Adsorption mechanisms typically follow Langmuir isotherm models, involving both physisorption and chemisorption, depending on the functional groups present.[36] Importantly, corrosion inhibition performance of plant extracts has been reported as comparable or even superior to conventional inhibitors such as chromates or phosphates, while offering a non-toxic and biodegradable alternative.[20]

Hybrid applications

An emerging strategy involves combining antioxidant/antimicrobial functions with corrosion inhibition, producing dual-function coatings. Plant extract-loaded epoxy or polyurethane coatings not only protect against microbial colonization but also prevent electrochemical corrosion, extending the service life of metallic structures.[6] For instance, tannin-based coatings demonstrated both antioxidant and corrosion protection, achieving efficiencies of 80–85% under accelerated salt spray tests.[6] For the Atakum flora, extracts from *Fumaria officinalis* (alkaloids) could be incorporated into epoxy coatings as bioactive anticorrosive additives, while Crocus extracts (crocin, safranal) may enhance UV and oxidative stability in PLA or PHBV films. This highlights how ethnobotanically relevant but underutilized plants can be valorized as sustainable engineering solutions.

Future perspective

I. Standardization of extraction protocols for reproducibility of inhibition efficiencies.

II. Mechanistic studies using electrochemical impedance spectroscopy (EIS), X-ray photoelectron spectroscopy (XPS), and atomic force microscopy (AFM) to understand surface interactions.

III. Scale-up validation for industrial coatings, particularly in packaging, biomedical, and marine applications.

IV. Integration into circular bioeconomy frameworks, where waste biomass streams are valorized into high-value bioactive additives.

Encapsulation and smart systems

Encapsulation technologies have become increasingly important in materials engineering, food science, and biomedical applications due to their ability to protect bioactive compounds, improve stability, and enable controlled release. Plant-derived bioactives, such as polyphenols, carotenoids, flavonoids, and essential oils, are often sensitive to light, heat, pH, and oxidation. Encapsulation provides a pathway to integrate these compounds into active packaging, functional foods, cosmetics, and drug delivery systems.[37]

Micro- and nanoencapsulation approaches

Techniques such as spray-drying, coacervation, liposome entrapment, nanoemulsions, solid lipid nanoparticles (SLNs), and electrospinning are widely employed for encapsulation of plant extracts.[7] Among these, nanoencapsulation offers superior bioavailability, targeted release, and enhanced absorption compared to conventional microencapsulation. For instance, encapsulation of curcumin in SLNs significantly improved its antioxidant stability and bioaccessibility in food matrices.[38] Similarly, encapsulation of essential oils in nanoemulsions reduced volatility and provided extended antimicrobial activity in packaging films.[39]

Applications in saffron and local MAPs

Saffron (*Crocus spp*.) carotenoids, particularly crocin and crocetin, are highly unstable under light and heat. Studies have shown that encapsulating these compounds in biopolymer matrices such as maltodextrin, chitosan, and whey protein improves their thermal and oxidative stability while preserving color and antioxidant activity.[7] These encapsulated systems are applied in cosmetics, nutraceuticals, and functional foods, extending the usability of saffron beyond its traditional culinary role. In the context of the Atakum flora, encapsulation strategies could also be applied to stabilize Fumaria alkaloids (sensitive to oxidation), Trachystemon mucilage fractions (for hydrogel reinforcement), and Ruscus saponins (for biomedical coatings). By designing encapsulation systems tailored to these local bioresources, their potential industrial applications can be significantly expanded.

Smart release and responsive systems

A recent frontier in encapsulation is the development of stimuli-responsive or "smart" systems, which release bioactives in response to changes in pH, temperature, moisture, or microbial activity. For example, pH-sensitive encapsulated phenolics can be triggered to release in the intestinal tract, enhancing functional food applications.[32] Similarly, antimicrobial essential oils encapsulated in cyclodextrins demonstrated controlled release in humid environments, enabling active packaging films that respond to food spoilage conditions.[40] These smart systems can also be engineered to serve as biosensors, changing color or fluorescence upon release of bioactive markers. Crocin-loaded nanocapsules, for example, can serve dual functions as antioxidants and as optical indicators for UV degradation in packaging materials (Sharma et al., 2020).

Future perspectives

The integration of encapsulation and smart release systems into sustainable materials provides multiple opportunities:

I. Active packaging: Encapsulation of plant extracts in PLA/PHBV films for antioxidant, antimicrobial, and UV protection.

II. Biomedical hydrogels: Controlled release of plant-derived anti-inflammatory agents (e.g., Ruscus saponins).

III. Nutraceuticals: Nanoencapsulation of phenolics to improve solubility and intestinal absorption.

IV. Sensor-enabled materials: Smart packaging films that respond to oxidation, spoilage, or microbial contamination.

V. For the full valorization of Atakum's MAPs, encapsulation technologies offer a pathway to bridge traditional plant use with modern nanotechnology and responsive material systems.[41-44]

Conclusion and evaluatıon

The coastal forest flora of the Atakum region provides a unique combination of botanical diversity and phytochemical richness, offering promising opportunities for sustainable material development. Although the species examined—Trachystemon orientalis, Arum maculatum, Galium aparine, Borago officinalis, and *Crocus spp*.—have long been recognized in ethnobotanical contexts, their potential contributions to biopolymer research, hydrogels, bioactive films, and natural fiber–based materials remain underexplored. This review highlights the need for systematic characterization, standardized analytical approaches, and cross-disciplinary collaboration to unlock their full value. The regional dimension is especially significant: utilizing locally abundant plant resources could support new economic pathways, promote low-impact production models, and strengthen innovation capacity in the Black Sea region. Future research should prioritize: (1) establishing consistent analytical protocols; (2) evaluating safety and toxicological thresholds; (3) assessing processability for material applications; and (4) integrating ecological sustainability into resource management. Addressing these challenges will allow these native species to transition from traditional use to high-value technological applications. Ultimately, leveraging the natural assets of the Atakum coastal ecosystem presents a strategic opportunity—not only for scientific advancement but also for regional economic development through sustainable and innovative material solutions.

Acknowledgments

None.

Conflicts of interest

None.

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