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SCIENCE PARK
PUBLISHER

New Horizons Journal of Basic and Applied Sciences

Algal and bee-derived compounds: Bioactives for cosmetics and therapeutic applications

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Abstract

Algae and honeybee products are showing up more and more in skincare and in topical or adjunctive treatments because they're rich, natural sources of active molecules. Macroalgae and microalgae produce sulfated polysaccharides, phlorotannins, carotenoids, and peptides—compounds known for antioxidant, anti-inflammatory, photoprotective, brightening, and moisturizing effects. From the beehive, medical-grade honey, beeswax, and bee venom (BV) stand out for supporting wound repair and calming inflammatory skin conditions thanks to their antimicrobial, anti-inflammatory, immunomodulatory, barrier-strengthening, and pro-regenerative actions. This review pulls together recent progress on the chemistry, mechanisms, delivery systems, and real-world uses of algae- and bee-derived ingredients. Meta-analyses suggest that medical-grade honey can modestly yet meaningfully speed healing in chronic wounds, while combinations of bee products are gaining traction for acne care and biofilm control. Crucially, sustainable sourcing and careful standardization are making it easier to create products that perform as both effective cosmetics and credible therapeutics. With better evidence and formulation practices, these algae- and bee-based actives can move from promising products to fully evidence-backed ingredients in modern skincare and medicine.

1. Introduction

The cosmetics industry is one of the most rapidly expanding sectors of the economy. Consumer demands have changed to reflect the modern lifestyle, which is based on technological advancements and a better understanding of how various factors influence people's fitness and health. Cosmetics made from natural, eco-friendly ingredients with positive health benefits are becoming increasingly popular. The use of antimicrobial chemicals as ingredients in cosmetics ensures their longevity and safety. Natural substances with these properties, such as polyphenolic compounds, peptides, essential oils, and plant extracts, can replace artificial ingredients in cosmetics. These compounds offer antimicrobial, anti-inflammatory, and calming properties,

increasing the product's value [1]. For thousands of years, people have used bee products to treat diseases, provide nutrition, and protect their health. Their valuable contribution to human life makes them desirable due to the bioactive components they contain. Traditional medicine, particularly bee products and medicinal plants, has gained popularity in the field of complementary medicine in recent years as people become more interested in natural nutrition and alternative therapies. Acupuncture, apitherapy, ozone therapy, music therapy, cupping-leech therapy, chiropractic, prolotherapy, osteopathy, worm therapy, hypnosis, reflexology, homoeopathy, and bee products are all used to treat blood circulation, the nervous system, tumours, arthritis, rheumatism, and skin diseases. Bees' primary products include

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honey, propolis, pollen, bee bread, royal jelly, beeswax, and BV [2].

Bee products such as honey, propolis, royal jelly, bee pollen, bee bread, BV, and beeswax have been used in traditional medicine for centuries due to their numerous health benefits. Bee products have recently gained popularity in the cosmetics industry due to their potential skin and hair benefits. Bee products can be used in a variety of cosmetics, including creams, serums, masks, shampoos, and hair conditioners. They can be used as ingredients in formulations or as standalone products [3]. BV is a common toxin released by the stingers of honeybee workers. Many cultures have long been drawn to BV and BV therapy, and extensive research has been conducted on the subject in recent decades. Today, BV is used to treat a variety of skin conditions such as vitiligo, psoriasis, alopecia, acne vulgaris, and atopic dermatitis. BV is commonly used in face masks, topical cosmetics, and wound dressings to promote healing. However, because BV can cause an immune system reaction in some people, its safety as a treatment option has been questioned. The documented adverse effect is explained by the possibility that BV-induced skin reactions can progress to severe immunological reactions, such as anaphylaxis, which typically resolve over several days [4]. Because of the increased demand and widespread use of cosmetics in daily life, global industrial production has increased. Formulations contain both organic and inorganic ingredients, including parabens, phthalates, sulphates, and others. Because of their persistence and ability to accumulate in various parts of the ecosystem, these substances are frequently the primary cause of ecological problems [5].

Macro- and microalgae are promising candidates for the development of pharmaceutical preparations, whether as medicines or nutraceuticals, because they contain a variety of physiologically active compounds that are highly desirable for disease prevention. In vitro and in vivo studies have been conducted to investigate the potential mechanisms of action of algae, as epidemiological studies suggest that eating them can protect against conditions such as allergies, cardiovascular disease, cancer, obesity, diabetes, high blood pressure, atopic dermatitis, and Alzheimer's disease [6]. The cosmetics industry has been working to develop products containing natural, renewable ingredients. Biosurfactants can help meet this need. A growing consumer market and cosmetics industry

are interested in these natural compounds because they are renewable, biodegradable, non-toxic, or low-toxicity, posing little risk to people or the environment [7]. The primary goal is to evaluate bioactive compounds found in bee products such as propolis, honey, and venom, as well as macro- and microalgae, for biofilm disruption and antimicrobial activity. This work will lead to the development of natural-based cosmetics that are safe, stable, and effective. Additionally, it aims to develop innovative, eco-friendly cosmetic solutions that not only enhance product safety and durability but also improve the health of skin and hair.

2. Algae-derived compounds

Marine macro and microalgae (including cyanobacteria) produce an unusually rich repertoire of compounds with antibacterial, antiviral, antifungal, and anti-inflammatory effects relevant to human disease and skin health [8]. Algae have long been recognised and used for its therapeutic properties. They have shown efficacy in the treatment of various respiratory conditions, including bronchitis, colds, and persistent cough, helminthiasis, weight management, enlarged thyroid gland, and gout, as well as topical ointments and anaesthetics. These characteristics stem from the biologically active substances found in algae [9]. Algae contain various proteins and amino acids, including glycoproteins, metalloproteins, and exogenous amino acids [10]. Researchers assert that algae possess essential unsaturated fatty acids. Cyanobacteria have various secondary metabolites, including flavonoids, terpenoids, and phenolic acids. Pharmacological studies indicate that these cyanobacteria and microalgae have significant effects in both in vitro and in vivo settings. Clinical trials are rare and understudied, with anticancer testing primarily limited to in vitro methods and a few in vivo experiments. To establish the safety of these bioactive compounds, each research effort into their anticancer potential must rigorously evaluate their clinical efficacy and toxicity. Extensive clinical research is required to better understand their therapeutic potential and facilitate the development of new cancer treatment approaches [11].

Currently, microalgae can be used to bioremediate a wide range of contaminants from residential, commercial, and agricultural environments. Microalgae-mediated treatment has several advantages over traditional wastewater treatment

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plants, including CO_2 reduction during cultivation and the possibility of using biomass as a feedstock for biodiesel or ethanol production. Some studies provide an overview of methods and treatment systems, as well as a comprehensive synopsis of recent research and developments in algal-mediated PPCP removal in wastewater treatment processes [12]. A detailed analysis and evaluation of the factors influencing PPCP removal from aqueous media are presented. Furthermore, other studies have investigated various microalgal strains to improve the efficiency of future processes. Additionally, another study has examined how microalgae can help reduce the negative environmental effects of pharmaceutical and personal care products (PPCPs), as well as the spread of antibiotic-resistant bacteria [13].

Seaweeds are moisturising, anti-inflammatory, and regenerative, and they contain various cosmetic compounds, including vitamins, minerals, trace elements, amino acids, and antioxidants (Table 1). The term "blue cosmetics" refers to a category of products that contain natural active ingredients and command a sizable market share among major global cosmetic brands. To be considered environmentally sustainable, algae-based products must use ecologically responsible harvesting, production, and extraction practices (Figure 1) [14]. As the cosmetics industry expands, new products must meet higher safety and efficacy standards. The marine environment fosters microorganisms with unique metabolic processes and adaptation strategies, leading to natural products characterised by distinct structures, high diversity, and significant biological activities compared to terrestrial organisms. Natural products are usually non-polluting and safe. As a result, significant efforts have been made to identify natural, safe, and effective cosmetic ingredients that do not harm marine microorganisms. Nonetheless, the unique environmental requirements of marine microorganisms make their cultivation difficult or impractical. This problem can be solved effectively using metagenomics technology. Cosmetic manufacturers are increasingly using marine species for biotransformation, which leads to more environmentally friendly products [15].
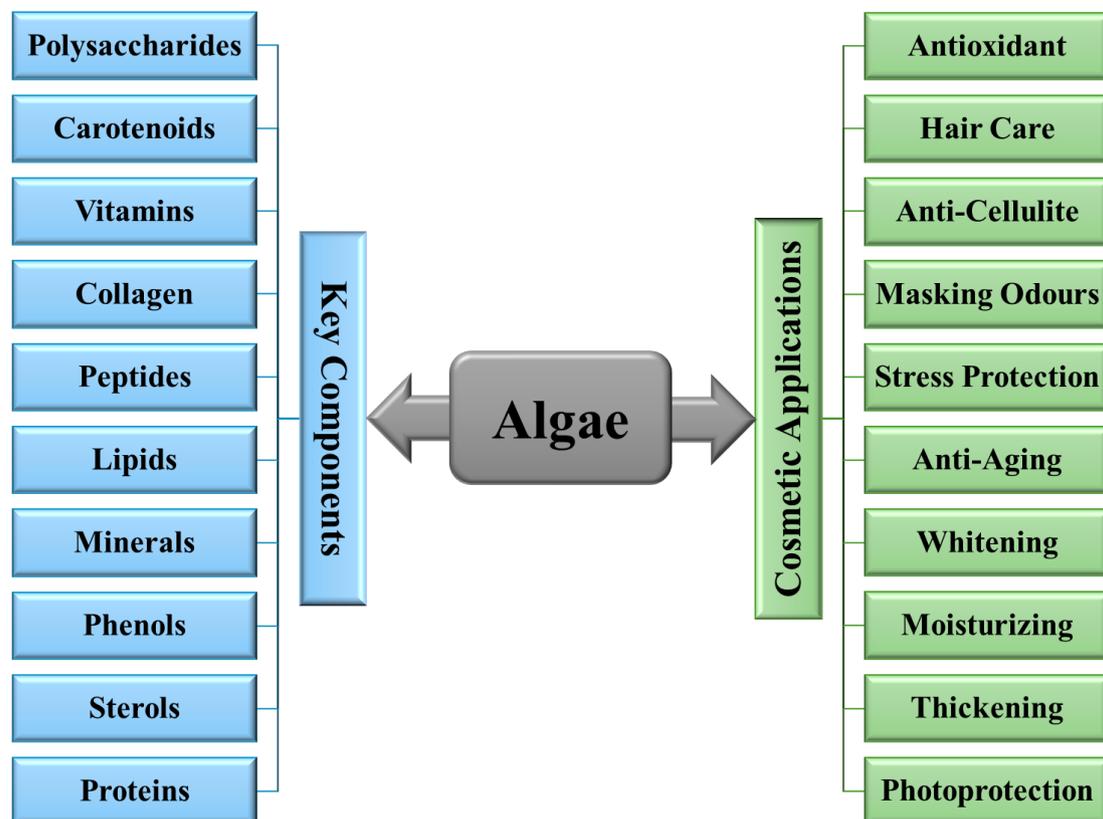
Figure 1. Algae components and cosmetic applications.

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Red algae, known as Rhodophyta, are becoming increasingly popular for their medicinal properties. Red algae, which number around 7000 species, are a rich source of bioactive compounds used in the food, cosmetic, and pharmaceutical industries. Red algae-derived bioactive compounds have a wide range of activities, including antimicrobial, antiviral, antitumor, antioxidant, anti-obesity, anti-inflammatory, antidiabetic, anticoagulant, antiallergic, and analgesic properties. These compounds include sulfated galactan, carrageenan, peptides, phycobiliproteins, lectins, protein, bromophenol, and cholesterol. Recent advances in the use of red algae suggest that they could be used as fluorescent dyes in photodynamic therapy, nutraceutical formulations, bone tissue engineering composites, nanotechnology-based drug delivery systems, and cosmetic additives [16]. This section also discusses algae as potential therapeutic interventions, including their various bioactive components and applications [17]. The specific percentages of phenolics and flavonoids in propolis (flavonoids 8–15%, phenolic acids 12–20%), the peptide melittin (40–60% of dry BV), and the lipid-rich fractions of beeswax (esters 70–80%, hydrocarbons 10–15%) are all bee-derived compounds. The primary fatty acid in royal jelly, 10-hydroxy-2-decenoic acid (2–6%), and the protein fraction (major royal jelly proteins, 12–15%) have been elucidated, and are enhanced by the integration of these quantitative values with specific cosmetic and therapeutic applications, including skin hydration, antimicrobial protection, anti-inflammatory activity, and dermal regeneration (Table 1) [18].

3. Bee-derived compounds

Skin tissue regeneration is a major concern for many patients, as complications during the healing process can result in negative outcomes. Sustainable materials derived from natural products, such as honey and its derivatives, propolis, royal jelly, bee pollen, beeswax, and BV, may offer alternatives to traditional treatments. Their potential for dermal tissue regeneration is significant, and they have notable antibacterial inhibitory properties [19]. Pharmaceutical research shows that combining bee products with conventional medications may improve outcomes (Table 1). The benefits include the reduction of side effects and the preservation of efficacy by using low doses of chemotherapy, anti-

inflammatory, or antibiotic agents. Numerous studies show that bee products may be effective alternatives to antibiotics in terms of their antimicrobial activity and efficacy; however, more research is needed to assess the potential of topical mixtures containing honey, royal jelly, and propolis. Bee products appear to address each other's shortcomings, and their combination may improve wound healing [20].

BV derived from honeybees, has been used as a natural remedy for various ailments. BV was found to contain approximately 20 bioactive compounds that are responsible for its unique properties, which include antitumoural, antinociceptive, antirheumatic, anti-inflammatory, neuroprotective, antiarthritic, antimicrobial, and antidiabetic effects. These substances can be classified as peptides, bioactive amines, sugars, phospholipids, enzymes, amino acids, pheromones, and minerals. Melittin is the primary peptide in its composition, with apamin and adolapin ranking second and third, respectively. Melittin accounts for 40–60% of the BV composition [19]. Bees serve as bioindicators, contribute to biodiversity conservation, provide essential ecosystem services, and produce a wide range of products. This work examines the primary components of bee products in depth, with a focus on their biological potential and health benefits. It discusses the nutritional value, bioactive profile, and associated benefits of these products. It also includes a quantitative review of the literature, with a particular emphasis on honey and health, as well as other bee products that are analysed using various databases [21]. The specific percentages of phenolics and flavonoids in propolis (flavonoids 8–15%, phenolic acids 12–20%), the peptide melittin (40–60% of dry bee venom), and the lipid-rich fractions of beeswax (esters 70–80%, hydrocarbons 10–15%) are all bee-derived compounds. The primary fatty acid in royal jelly, 10-hydroxy-2-decenoic acid (2–6%), and the protein fraction (major royal jelly proteins, 12–15%) have been elucidated. These findings are significantly enhanced by the integration of these quantitative values with specific cosmetic and therapeutic applications, including skin hydration, antimicrobial protection, anti-inflammatory activity, and dermal regeneration (Table 1) [22].

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Table 1. Analysis of bee and algae products, therapeutic applications, and cosmetic applications.

Source	Bioactive compounds	Chemical class	Therapeutic applications	Cosmetic applications	References
Honey	Enzymes (Glucose Oxidase)	Monosaccharides, Enzymes, Phenolic Compounds	Wound Healing antibacterial, debriding agent	Moisturizing humectant, emollient	[23, 24]
Propolis	Flavonoids Phenolic Acids Terpenes	Polyphenols, Terpenoids	Anti-inflammatory Antimicrobial Liver Protection Radiation Protection	Anti-aging: (antioxidant, collagen stimulation)	[25]
Bee Venom	Melittin Apamin Phospholipase	Peptides, Enzymes	Antiviral/Bacterial	wrinkles and boosting collagen	[26]
Alginate	Alginic Mannuronic Guluronic acid	Polysaccharide	Gut Health (prebiotic, anti-reflux)	hydrating masks viscosity modifiers	[27]
Spirulina	Phycocyanin Linolenic Acid	Phycobiliprotein, PUFA, Tetraterpenoids	Nutraceuticals Strong antioxidant; anti-inflammatory	moisturizing and anti-acne effects	[28]
Fucoidan	Fucoidan	Sulfated Polysaccharide	Anti-inflammatory & Anticancer: Inhibits leukocyte migration	Anti-aging: potent antioxidant against UV damage	[29]

4. Cosmetic applications

Bee products such as honey, pollen, and BV have been used in dermatology and wound care, with numerous studies demonstrating their skin-healing properties [30]. Bee products are used in many medications and cosmetics. Honey has antimicrobial and regenerative properties due to its high osmolarity, hydrogen peroxide content, and lysozyme concentration. Bee pollen contains an abundance of vitamins, flavonoids, hydroxy acids, and unsaturated fatty acids. Beeswax is used primarily in cosmetics as an emulsifier. BV contains antiviral, antifungal, antibacterial, and anti-inflammatory properties. BV contains all of these components. Each bee product contains unique active compounds that distinguish it from the others [3]. Creams, serums, masks, shampoos, and hair conditioners are some examples of cosmetics that can be made with bee products. They can be used alone or as constituents in different formulations [31].

Beeswax is widely used in cosmetics manufacturing (Figure 2), particularly as a thickening agent for occlusives. When combined with substances like borax, it acts as an emulsifying agent. Honey is extracted from honeycombs by melting the wax and removing impurities using methods such as steam, electricity, or solar extraction before it is used in cosmetics. Cosmetics are made from white (Cera alba) and yellow (Cera flava) waxes. After processing, it serves as the foundation for the formulation of lipsticks, emollient skin creams, lotions, ointments, and other cosmetic products. Beeswax alters the physical properties of cosmetic formulations, increasing the hardness and glossiness of lipsticks while improving their colour, texture, and application [32]. Honey is made up of about 200 compounds, the majority of which are sugars (fructose 25-45% and glucose 20-40%), water, and a variety of other components such as proteins, amino acids, enzymes, vitamins, minerals, ash, organic acids, and phenolic and flavonoid compounds, all of which contribute to its biological efficacy [33].

The constituents of BV, or apitoxin, have shown therapeutic benefits. Proteins (enzymes) and peptides are the main constituents, with melittin (the primary component of BV and apamin standing out. Following this, low molecular weight compounds such as phospholipids, biogenic amines (such as histamine and catecholamines), amino acids, sugars, volatiles
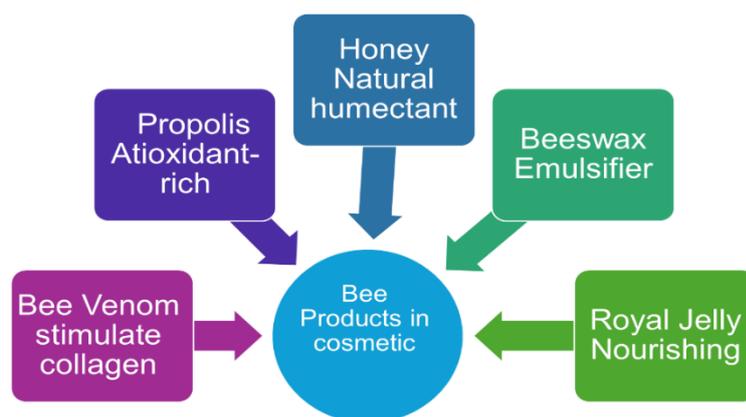
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(pheromones), and minerals are discussed [33]. Bees make bee bread by adding saliva to pollen and honey, fermenting it with enzymes for two weeks, and then storing it in honeycomb cells. It contains carbohydrates (24–35%), protein (20–22%), lipids (1–1.5%), minerals (2–3%), lactic acid (3–3.5%), and many vitamins. It contains coenzyme Q10, phenolic compounds, and α-tocopherol, which contribute to antioxidant activity. It contains more lactic acid and vitamin K than bee pollen, as well as having a higher nutritional value and digestibility [2].

5. Therapeutic applications

In today's health-conscious society, there is a growing demand for natural products, especially those made from bees. Apiculture is the practice of raising honeybees in artificial hives for the purpose of gathering different bee products, particularly honey, bee bread, venom, pollen, propolis, and royal jelly. Often used as a wholesome food supplement and therapeutic agent, honey is regarded as the first natural sweetener ever found. Geographical features, climatic conditions, floral preferences, and floral sources all affect the quality and flavor of honey. The possible health advantages of honey, including wound healing, microbial inhibition, and its impact on various illnesses, are explained. Antimicrobial, antioxidant, anti-inflammatory, anti-cancer, antihyperlipidemic, and cardioprotective qualities are all demonstrated by honey (Figure 3) [34].

Products made from bees, such as honey, propolis, pollen,

venom, bee bread, and royal jelly, have been used as natural cures for a variety of illnesses since ancient times. Independent of the bee species, the varied composition and chemical characteristics of bee products contribute to their medicinal pleiotropy. This has prompted researchers to thoroughly examine these items' potential for therapeutic use, particularly honey. However, since nanotechnology research and applications have grown at an unparalleled rate, several types of nanomaterials have been used to increase the products' therapeutic efficacy. The green manufacturing of nanocarriers loaded with bee products or their extracts has drawn particular interest in an effort to preserve the products as natural and non-toxic medicines [35]. Honeybees produce a variety of products that benefit people in many ways. Because of their medicinal properties, honey, propolis, royal jelly, beeswax, BV, bee pollen, and bee bread have all been utilized as natural remedies since ancient times. Wounds, diabetes, gastrointestinal disorders, cancer, asthma, neurological disorders, and bacterial and viral infections have all been shown to be healed by these products [36]. Numerous studies have examined and substantiated the antibacterial and antibiofilm properties of honeybee products. However, little research has been done on their antiviral properties. Recent studies, however, have shown that they are effective against several viral infections, including SARS-CoV-2. Therefore, products made from honey bees may be used as substitutes to treat viral illnesses, particularly in cases where no efficient cure has been found [37].

Figure 2. Bees' products in cosmetics.

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Figure 3. Therapeutic benefits of bee products.

Many of these products' constituents have an impact on their pharmacological action. The primary bioactive substances found in honey are phenolic compounds, royal jelly proteins, oligosaccharides, and methylglyoxal. Jelleins, royalisin peptides, and hydroxy-decenoic acid derivatives, especially 10-hydroxy-2-decenoic acid, are found in royal jelly. These compounds have antibacterial, anti-inflammatory, immunomodulatory, neuromodulatory, metabolic syndrome-preventing, and anti-aging qualities. Propolis has many properties that are related to substances like phenethyl ester and caffeic acid. Melittin, apamin, and phospholipase A2 are among the peptides present in BV. Apart from its high vitamin content, bee pollen also contains phenolic compounds, sterols, and unsaturated fatty acids that have anti-inflammatory, anti-atherosclerotic, and antidiabetic effects. The components of hive products are therefore unique and distinct [22].

6. Regulatory framework for algal-derived ingredients

The regulatory framework for algal-derived ingredients differs by country and application. The U.S. Food and Drug Administration (FDA) regulates food safety, including algal products. Certain microalgal species and derivatives, including *Spirulina*, *Chlorella*, *Dunaliella*, *Haematococcus*, and *Schizochytrium*, can be designated as "Generally Recognised as Safe" (GRAS) [38]. The European Food Safety Authority (EFSA) is the primary entity responsible for food and feed safety, health, and nutrition in the European Union, with oversight provided by the European Commission and national authorities in member states. Before entering the market, products are risk-assessed and authorised [39]. Australia, New Zealand, and Canada each have their own regulatory agencies that oversee novel food ingredients, including those derived from microalgae [40].

All algae-derived ingredients must undergo comprehensive safety evaluations, which include toxicological testing, allergenicity assessment, and contamination analysis for heavy metals, toxins, and chemical residues [41]. Adherence to food safety and quality standards is essential, including hygiene, compositional integrity, and the absence of undesirable substances [39]. Products must be accurately labelled and, in many jurisdictions, require specific authorisation or notification before marketing, particularly if they are classified as novel foods or dietary supplements [39]. Some researchers have reported that the food industry requires approval for all production processes, materials, and protocols [42]. The absence of global regulations and well-defined rules for microalgae-derived bioactive chemicals complicates product safety, quality, and labelling. Regulatory clarity and harmonisation are essential for promoting international trade and building consumer trust [43]. Collaboration among regulatory authorities, industry, and academia is required to address these issues and ensure effective risk assessment and compliance [44]. Comprehensive toxicological assessments are required to confirm the safety of algal ingredients for human consumption. The allergenic potential is typically species-specific, and current data show that approved algal proteins are not significant allergens. Some species, particularly specific microalgae, can produce toxins, and their

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safety depends on cultivation and processing conditions [41]. Algae can accumulate toxic compounds from their surroundings, such as heavy metals, antibiotics, and dyes. The use of organic solvents in extraction processes can result in chemical residues that must be carefully controlled and monitored [45]. Cross-contamination prevention and culture purity maintenance are critical, especially for products like Spirulina. Continuous monitoring, thorough testing, and effective decontamination protocols are critical to ensuring product safety. In-depth research is required to assess the risks associated with chronic or subchronic exposure to algal supplements [46]. Standard guidelines and procedures, such as the Hazard Analysis Critical Control Point (HACCP), should be implemented to manage biological and chemical contamination throughout the production chain [47].

Extraction methods, including microwave-assisted, ultrasound-assisted, and enzyme-assisted techniques, must be assessed for efficacy and safety, particularly regarding the risks linked to high-pressure and high-temperature processes [48]. The European Committee for Standardisation (CEN) has established technical committees to develop standards for algae and algae products with the goal of improving supply chain consistency and market trust [49].

7. Role of artificial intelligence and machine learning

Artificial intelligence and machine learning are revolutionising the processes of discovering, characterising, formulating, and translating natural bioactives into cosmetics and pharmaceuticals (Figure 4). Computational methods allow for more efficient, cost-effective, and reproducible decision-making throughout the algae and bee product pipeline. These products have significant chemical diversity, complex mixtures, and batch variability, posing ongoing challenges ranging from strain selection and extraction to efficacy and safety assessment. Recent reviews and case studies in natural products science have highlighted the use of AI to improve bioactivity prediction, dereplication, omics-guided discovery, and ADMET/toxicity modelling, making this an appropriate inclusion in the current review [50]. In natural product research, artificial intelligence includes cheminformatics, such as quantitative structure-activity relationship (QSAR) models, molecular fingerprints, and generative models; multi-omics

integration, which includes genomics, metabolomics, and proteomics; and automation technologies such as automated machine learning (AutoML) and robotics. These approaches reduce trial and error, allowing for hypothesis-driven exploration of large, diverse datasets typical of natural extracts such as algal pigments, polysaccharides, and bee-derived polyphenols and peptides. Recent surveys emphasise the importance of high-quality, standardised multimodal datasets such as spectra, structures, and bioassays, as well as the use of knowledge graphs to integrate chemical, biological, and clinical evidence [50]. Data standards appropriate for AI, including metadata related to species, harvest seasons, processing, and analytic methods, should be implemented for algae and bee matrices to facilitate effective model training and equitable benchmarking [51].

Machine learning-based quantitative structure-activity relationship (QSAR) models have shown significant efficacy in predicting antioxidant and related activities in a variety of natural compounds and peptides, which are critical for cosmetic and therapeutic applications such as reactive oxygen species (ROS) scavenging and anti-inflammatory properties [52]. Recent studies show that Extra Trees and Gradient Boosting models achieve R^2 values of 0.75 to 0.78 for DPPH assays, while deep multimodal frameworks outperform with AUROC and AUPRC values greater than 0.90 for antioxidant peptide activity. These methods are easily applied to algal phycobiliproteins, carotenoids, bee-derived peptides, and polyphenols [53]. Untargeted LC MS/MS, combined with machine learning classification, such as SIRIUS-derived fingerprints, allows for the early identification of known scaffolds, preventing rediscovery and directing isolation efforts towards novel active compounds. An accuracy of more than 93% has been documented across various bioactive classes, which is especially relevant to microalgal metabolite libraries and fractions of bee products such as honey and propolis. Systematic dataset curation, analysis of applicability domains, and external validation are critical for reducing overfitting and ensuring that in vitro assays translate to formulation performance [54]. AI-assisted metabolomics identifies bioactive signatures and links phenotypes to metabolic pathways, allowing for the selective enrichment of antioxidant and anti-inflammatory metabolites and nutraceuticals. Reviews shed light on machine learning-

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enabled annotation, molecular networking, and pathway inference for connecting algal metabolomes to biological activities, while computational methods like docking and functional metabolomics aid in prioritising targets and mechanisms [55]. The mechanistic data for apitherapy are limited; however, AI-driven hive monitoring and health analytics generate high-resolution environmental and biological datasets. These datasets can be combined with the chemical profiles of honey, propolis, and royal jelly to investigate variability, contamination, and bioactivity trends across seasons and geographical regions. Multimodal neural networks that combine audio and visual signals have achieved more than 90% accuracy in assessing colony health, laying the groundwork for data-rich apicultural supply chains that provide safer and traceable cosmetic and therapeutic ingredients [56]. Interpretable deep learning is assisting in the discovery of "dark proteomes" and unannotated enzymes in microalgae, which may reveal novel biosynthetic pathways for cosmetic actives such as pigments and UV protective molecules. Machine learning models optimise growth conditions (light, nutrients, CO_2), harvest timing, and dewatering/drying processes for microalgae. This results in higher biomass and target compound yields while decreasing costs, which is critical for the scalability of cosmetic actives (carotenoids, polysaccharides) and therapeutic candidates. According to reports, productivity gains in AI-optimized environments range from 15% to 57%, with yield improvements of 20% to 43% [57]. Artificial Neural Networks/Support Vector Regression and hybrid AI algorithms outperform traditional response surface methodology in optimising extraction parameters (solvent, temperature, time, pH) for complex botanicals and food byproducts; these methodologies are directly applicable to algal pigments and bee-derived phenolics/proteins. AI-optimized extraction and bioprocess digitisation reviews highlight benefits in real-time control and sustainability, such as lower energy and solvent consumption [58]. AI platforms in cosmetics research and development can now predict texture, stability, shelf life, and efficacy based on ingredient-property relationships.

Simultaneously, computational toxicology models evaluate sensitisation risk and compatibility, which is especially important for natural mixtures like bee propolis and algal

extracts, which are prone to variability [59]. Computer vision models evaluate skin characteristics such as hydration, pigmentation, and acne, allowing for data-driven alignment of algal and bee actives with specific skin profiles and monitoring outcomes. Systematic reviews in dermatology and aesthetic skin health show significant progress as multimodal AI integrates imaging and clinical metadata. Nonetheless, establishing evaluation standards, diverse datasets, and fairness is critical [60]. Food and cosmetic safety reviews highlight the use of machine learning to predict intrinsic toxicity in bioactive foods and mixtures, emphasising the importance of modelling interactions found in multi-component bee and algal preparations [61].

AI can identify synergistic combinations of algal pigments and polyphenols with bee-derived peptides and polyphenols by analysing multi-omics and pharmacological networks. This approach is similar to developments in traditional medicine, in which network pharmacology combined with machine learning elucidates multi-component and multi-target actions. Drug repurposing pipelines that incorporate embeddings, graph neural networks, and transcriptomic signatures provide natural product researchers with scalable frameworks for prioritising indications and optimising combinations [62].

Precision apiculture, which uses IoT and machine learning for hive monitoring, enables standardised and traceable sourcing as well as batch quality assessment of bee products. This is accomplished by comparing colony health and environmental variables to the chemical profiles of honey, propolis, and royal jelly. Reviews and original works demonstrate the use of multimodal AMNNs for health prediction and sensor-rich "smart hives." [63] These data streams can improve ML models that predict bioactive yield and contaminant risk, resulting in better consistency for cosmetic and therapeutic applications [64]. AI and machine learning make it easier to identify species, optimise cultivation, and process microalgae, ensuring a steady supply of high-value compounds like astaxanthin, fucoxanthin, phlorotannins, and sulfated polysaccharides. Reviews summarise algorithms ranging from SVM to deep learning for detection, monitoring, harvesting, and purification. The integration of these algorithms with metabolomics and functional assays facilitates "design-make-test-learn" cycles for bioactive discovery [65].

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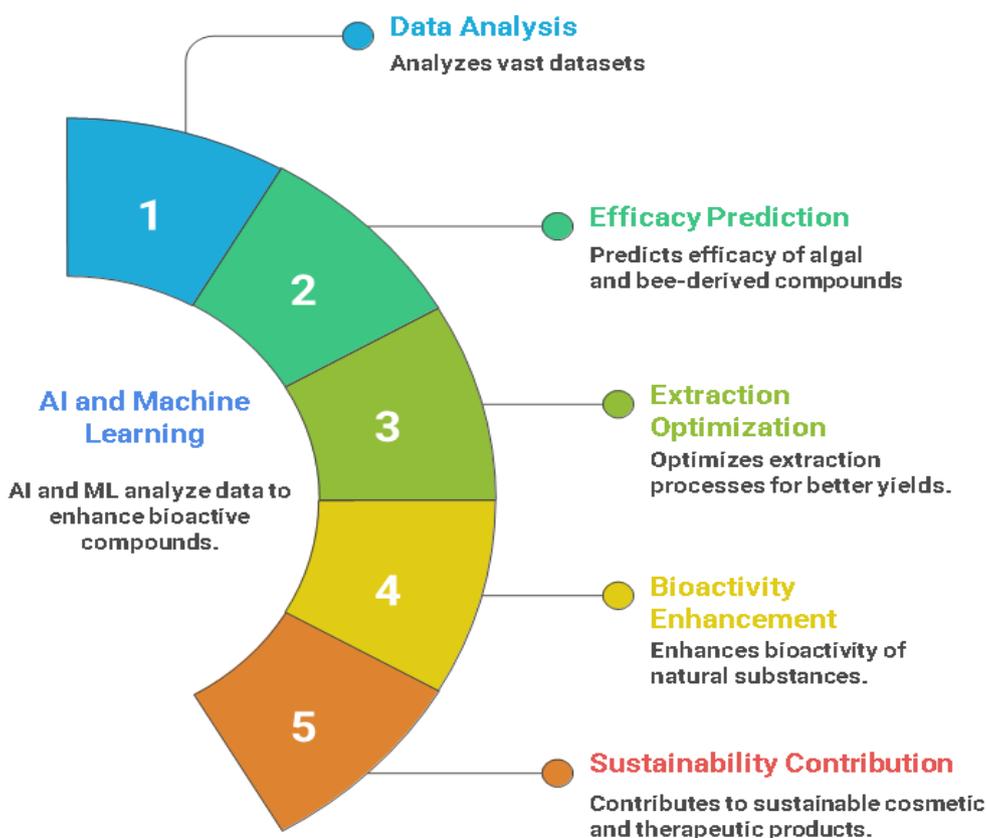
Figure 4. AI's impact on bioactive compounds.

Despite promising results, many AI applications involving natural bioactives face significant challenges, such as data scarcity and heterogeneity. Small and biassed datasets—often influenced by species, season, or extraction methods—limit generalisability. However, the use of knowledge graphs and standardised metadata could alleviate these concerns [51]. Model interpretability is a major concern, as regulators and clinicians require transparent explanations for safety and efficacy claims. This demand drives research into explainable AI and mechanistic integration, including functional metabolomics and target prediction. Validation gaps persist, as translating in silico predictions into clinical or cosmetic outcomes necessitates prospective, controlled studies with diverse populations and skin types, as well as extensive post-market surveillance. Policy and standards organisations are increasingly requiring evidence of model fairness, reproducibility, and lifecycle documentation, including data provenance and versioning, especially when AI is used in product claims or safety evaluations [59]. The combination of multi-omics, interpretable deep learning, and knowledge graph-driven reasoning creates comprehensive AI-enabled pipelines capable of identifying novel algal enzymes and metabolites, improving bee product quality through precision apiculture, and providing safer, personalised cosmetic and therapeutic formulations based on mechanistic evidence. Continuous advancement is based on accessible, thoroughly annotated datasets, stringent validation processes, and interdisciplinary collaboration among chemists, data scientists, dermatologists, apiculturists, and regulatory specialists.

8. Toxicity and safety considerations of bee and algae-derived compounds

While bee products have significant therapeutic potential, their safety profiles vary depending on dosage, route of administration, and individual sensitivity. BV is the most powerful and potentially harmful bee product. Melittin, its primary toxic component, can cause hemolysis, rhabdomyolysis, and acute kidney injury at high doses due to its nonspecific membrane-lytic activity [66]. Phospholipase

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A2 (PLA2) is a major allergen that causes severe IgE-mediated anaphylaxis in sensitized individuals. Local reactions to BV therapy (for example, arthritis) include pain, redness, and swelling, while systemic reactions range from urticaria to life-threatening anaphylaxis. However, the toxic effects are dose-dependent. In controlled, sub-lytic doses, melittin's membrane-disrupting property is selectively used against cancer cells or microbes, demonstrating a therapeutic window. The safety of algal compounds is paramount, especially considering their increasing use in nutraceuticals, pharmaceuticals, and cosmetics. Toxicity can arise from the bioactive compounds themselves or from contaminants accumulated during growth. Heavy Metal and Toxin Contamination: Microalgae and macroalgae can bioaccumulate heavy metals (e.g., arsenic, lead, cadmium, mercury) and, in the case of cyanobacteria, produce powerful hepatotoxins (microcystins) and neurotoxins (anatoxin-a, saxitoxins) [67]. Rigorous sourcing, cultivation control, and purification processes are required to ensure consumer safety. The regulatory limits for contaminants in algal products must be strictly enforced. Spirulina (Phycocyanin): According to the US FDA, Arthrospira platensis (Spirulina) is generally recognized as safe (GRAS). Toxicity studies have found no observed adverse effect levels (NOAEL) at extremely high doses [68]. However, the quality of commercial products varies, and contamination with toxic cyanobacteria (such as Microcystis) is a known risk, emphasizing the need for dependable, certified suppliers.

This study covers the current state of knowledge about bioactive derived from algae and bees, with a focus on their potential uses in medicine and cosmetics [69]. In addition to listing compounds and the uses for which they are employed, it is crucial to assess their relative merits, pinpoint the obstacles to translation, and create strategic plans that promote responsible innovation [70]. Furthermore, it provides an all-encompassing perspective by incorporating crucial subjects like safety, efficacy, sustainability, formulation science, regulatory environments, consumer acceptance, and methodological rigour [71]. Algae produce a wide range of bioactive substances, including polysaccharides, pigments, phenolics, sterols, and long-chain polyunsaturated fatty acids [69]. Enzymes, organic acids, phenolic and flavonoid complexes, and trace amounts of lipids are present in all bee

products, including honey, propolis, royal jelly, pollen, and venom [72]. All these products come from bees. Algal compounds primarily function as antioxidants, photo-protectants, moisturisers, immunomodulators, and anti-inflammatory agents [69]. Bee-derived compounds, on the other hand, possess antimicrobial activity, wound healing, barrier restoration, and immunomodulatory properties [72]. Algae work by scavenging reactive oxygen species and absorbing ultraviolet light [69]. Bee products, on the other hand, work by disrupting membranes, interfering with quorum sensing, and stimulating tissue repair mechanisms such as growth factor action and matrix remodelling [73]. This complementarity enables combination strategies in dermo-cosmetics and topical therapies [72]. Bee products can cause allergic reactions, particularly if you are allergic to bee proteins or venom [73]. To strike a balance between efficacy and tolerability, both categories necessitate rigorous testing of raw materials, purification processes, and formulation design, particularly in leave-on cosmetics and chronic topical therapies [70].

The combination of algae and bee-derived bioactive can produce multimodal formulations. Combining an algal antioxidant with a bee antimicrobial component, such as propolis extract, can help protect against oxidative stress and reduce microbial burden in acne-prone or compromised skin [72]. Algal polysaccharides have film-forming, humectant, and rheological properties that help formulations stay stable and improve skin feel [71]. Bee-derived matrices also exhibit bio-adhesion and wound-interface activity, as seen in honey gels [73]. Although many algae and bee compounds are effective on their own, there has been little systematic research into their combined use, particularly dose-response, mechanistic synergy, and safety [70]. To advance from theoretical synergy to practice-changing evidence for specific indications like photoaging, atopic dermatitis, and diabetic ulcers, extensive preclinical and clinical trials are required [69]. Plant preferences and concerns about bee welfare may limit the use of bee products in certain markets [72]. Clear sourcing policies, third-party certifications, and ethical alternatives, such as synthetic or recombinant analogues of bee peptides, can all improve accessibility [73]. Algae-based formulations can be classified as plant- or marine-derived solutions; however, more information on cultivation methods

is needed [70].

9. Current advancements and challenges

Discovery is moving fast for both algae and bee-derived ingredients: new algal antioxidants and photoprotectors are being identified with modern "omics" tools, and we understand much better how hive products like medical-grade honey, propolis, royal jelly, beeswax, and even BV support the skin's barrier, fight microbes, and encourage repair. Early clinical signs are encouraging honey dressings can modestly speed the healing of chronic wounds, and propolis based formulas show promise for acne, while greener delivery systems (such as hydrogels, film forming gels, and encapsulated algal extracts) are improving stability and targeted release. The big hurdles are uneven extract quality, not enough large, well-designed trials, and safety gaps (for example, iodine or heavy metals in some seaweeds and allergenicity with BV), plus the need for clear labelling and claims that match the evidence. The sustainability story is strong seaweed extracts often carry a lower footprint, and microalgae can even help clean wastewater but to turn these actives from "promising" into truly evidence-backed cosmetics and therapies, the field needs standardised markers, robust human studies, and transparent, traceable supply chains.

10. Conclusions and benchmark future prospects

Compounds derived from algae and bees have progressed from potential natural extracts to reliable sources of bioactive ingredients for skincare and adjunctive therapy, with consistent antioxidant, anti-inflammatory, photoprotective, antimicrobial, barrier-supportive, and pro-regenerative properties. Future advancements will be based on improved standardisation, routine control of contaminants and allergens, and regulations that are consistent with claims. To further enhance the field, it must produce at least two multicentre, adequately powered randomised controlled trials for chronic wound care, comparing medical-grade honey to standard care, and for acne, using core outcome sets, mechanistic biomarkers, and cost-effectiveness analyses. Green delivery systems should be extended, such as nanohoney hydrogels, propolis film-forming gels, and encapsulated algal actives,

while incorporating digital traceability. Achieving these benchmarks will establish algae- and bee-derived actives as dependable, reproducible, and socially responsible ingredients in modern cosmetics and therapeutics.

Author's contributions

Gehad M. Mahran, Omar Mohammad Atta, Khalifa S.H. Eldiehy and Abdel Kareem S. H. Mohamed: Conceptualization, Literature review, writing-Original draft preparation Graphics and Software, Writing- Reviewing and Editing.

Funding

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

No such data is used.

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