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Review

Plant-Derived Bioactive Compounds: One Health Perspective

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Abstract

This review, within the One Health framework, compiles information on plant-derived bioactive compounds and emphasises their multifunctional role in improving environmental, animal, and human health. These compounds support sustainable health and ecological stability by influencing biological and environmental processes. Data from literature research are combined to explain the mechanisms and potential uses of different key bioactive compounds. Mechanistic insights focus on their capacity to regulate oxidative stress, inflammation, and microbial balance, linking these effects to therapeutic benefits in human health, enhanced animal productivity, and environmental sustainability. These compounds show antioxidant, anti-inflammatory, antimicrobial, and metabolic activities, helping prevent chronic diseases, strengthen immunity, and reduce reliance on antibiotics and pollution. Examples like quercetin, resveratrol, and curcumin demonstrate their roles in modulating inflammatory and metabolic pathways to foster sustainable health and ecological balance. Bioactive compounds are linked to the One Health strategy, providing benefits across biological systems. Nonetheless, challenges such as variability, bioavailability, and standardization remain. Future directions should aim to develop sustainable extraction and formulation methods, leverage omics technologies and artificial intelligence for discovery and characterization, and foster industry partnerships to validate these compounds and secure global regulatory approval.

Keywords: One Health; natural products; bioactive compounds; sustainability

Academic Editor: Antonios E. Koutelidakis

Received: 31 October 2025
Revised: 24 December 2025
Accepted: 25 December 2025
Published: 29 December 2025

1. Introduction

The One Health approach, recognised by the World Health Organization (WHO) and the Food and Agriculture Organization of the United Nations (FAO), emphasises the interconnection between human, animal, and environmental health and highlights the need for integrated strategies to tackle global challenges [1]. Within this context, natural bioactive compounds, produced by microorganisms, marine organisms, and plants, have proven to be multipurpose agents that promote harmony between human, animal, and environmental systems. For instance, microorganisms remain the primary industrial source of antibiotics and fermentation-derived products with antimicrobial, anticancer, and immunomodulatory activities [2–6]. Marine organisms provide structurally unique metabolites shaped by extreme environmental pressures, yielding promising agents with antitumour, antiviral, and anti-inflammatory properties, as well as broad biotechnological applications [7–14]. Lastly, plants represent the most accessible and renewable reservoir of bioactive compounds; their availability, cultural acceptance, and compatibility with sustainable production systems make plant-derived bioactive compounds particularly relevant for the One Health objectives [15].

Plant-derived bioactive compounds have been studied due to their antioxidant, anti-inflammatory, antimicrobial, immunomodulatory, and metabolic regulatory properties, which sustain their role for chronic disease prevention, immune strengthening, microbial homeostasis, and reduced dependence on synthetic chemicals [16–18]. From a One Health perspective, these benefits extend beyond human medicine. In animal health, plant-derived bioactive compounds are being explored as performance enhancers and as alternatives to antibiotics, reducing the selective pressure that drives antimicrobial resistance [19]. At the environmental level, they can influence soil microbial communities, contribute to bioremediation, and improve productivity in agri-food systems [20,21]. Examples such as quercetin, resveratrol, and curcumin prove how modulation of oxidative, inflammatory, and metabolic pathways can translate into human health advantages, livestock productivity, and ecological resilience [22]. Despite this potential, important challenges remain: chemical variability, influenced by genetics, cultivation, and processing, delays standardization and reproducibility, while low stability or bioavailability can limit translation into effective products [23,24]. Progress, therefore, depends on sustainable extraction and formulation technologies, omics-based characterization, artificial-intelligence-driven discovery, and coordinated industry–academic partnerships [24,25]. Harmonised regulatory frameworks will also be essential to validate safety, efficacy, and ecological impact [24].

This review aims to gather and critically assess the role of plant-derived bioactive compounds, particularly the polyphenols, highlighting their multifunctionality and potential contributions to human, animal, and environmental health in accordance with the One Health approach. It will explore different mechanisms of action by which these bioactive compounds are involved, as well as emerging applications, such as natural preservatives and therapeutic advancements, while identifying the gaps that must be addressed to improve this field.

2. Plant-Derived Bioactive Compounds: An Overview

Bioactive compounds are defined by their biological activity rather than their origin, and include any molecule, whether natural or synthetic, that interacts with living systems to induce physiological or pharmacological effects [26,27]. As previously mentioned, bioactive compounds are organic molecules biosynthesised by living organisms, such as plants, microorganisms, and marine species [26,27]. These compounds are commonly classified into primary, secondary, and tertiary metabolites, based on their biological roles [26–29]. Primary metabolites (PMs) are essential for growth, development, and reproduction, including carbohydrates, lipids, proteins, and nucleic acids [30]. They take part in vital processes such as photosynthesis, respiration, cell structure formation, and function as signalling molecules (e.g., hormones and growth regulators like auxins and gibberellins) [30]. On the other hand, secondary metabolites (SMs) are not directly required for growth, but they confer ecological advantages, such as defence and adaptation [31,32]. They include phenolics, alkaloids, terpenoids, flavonoids, glycosides, and others, with bioactive properties relevant to medicine, agriculture, and biotechnology [23,25–27,33,34]. SMs arise from complex and integrated biosynthetic networks responsive to environmental stimuli [29]. Finally, tertiary metabolites (TMs) result from combinations or modifications of PMs and SMs with proteins, sugars, or lipids [32]. They are involved in embryogenesis, seed development, and stress adaptation, influencing metabolic balance [35]. Many natural compounds containing these metabolites exhibit anti-inflammatory, anticancer, and anti-ageing properties, underscoring their significant biomedical importance [28,29].

The plant kingdom comprises a vast diversity of species capable of producing structurally complex and biologically active metabolites, including carotenoids, biogenic amines, dietary fibre, bioactive peptides, vitamins, and polyphenols [36], as represented in Figure 1. Despite this, only 6% of plant species have been pharmacologically investigated, and approximately 15% have been phytochemically characterised [30,31]. Plants synthesise more than 200,000 metabolites, with applications in pharmaceutical, agrochemical, and food industries [25,37]. Compared to synthetic molecules, plant-derived products have greater structural diversity, higher molecular rigidity, and multiple chiral centres contributing to enhanced selectivity and pharmacokinetic performance [23]. Nearly 25% of modern pharmaceuticals and over 60% of anticancer and antimicrobial agents are obtained from plant natural products [24,38]. However, yield limitations, ecological dependence, and high research costs constrain large-scale exploitation, highlighting the need for biotechnological and metabolic engineering approaches to enhance production [39].

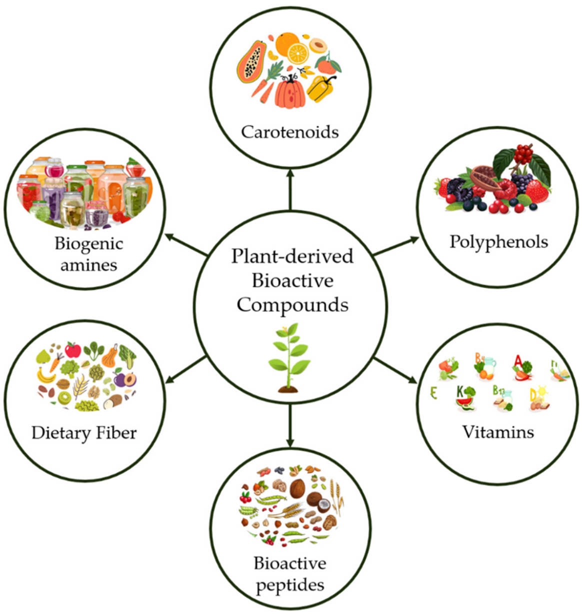

Figure 1. Synthesised overview of plant-derived bioactive compounds.

This review focuses on plant-derived bioactive compounds, namely polyphenols, SMs whose structural diversity and biological relevance have made them important sources of dyes, flavours, fragrances, and, notably, pharmaceuticals [25,37,40,41]. This class is divided into four subclasses, flavonoids, lignans, phenolic acids, and stilbenes [42], represented in Figure 2.

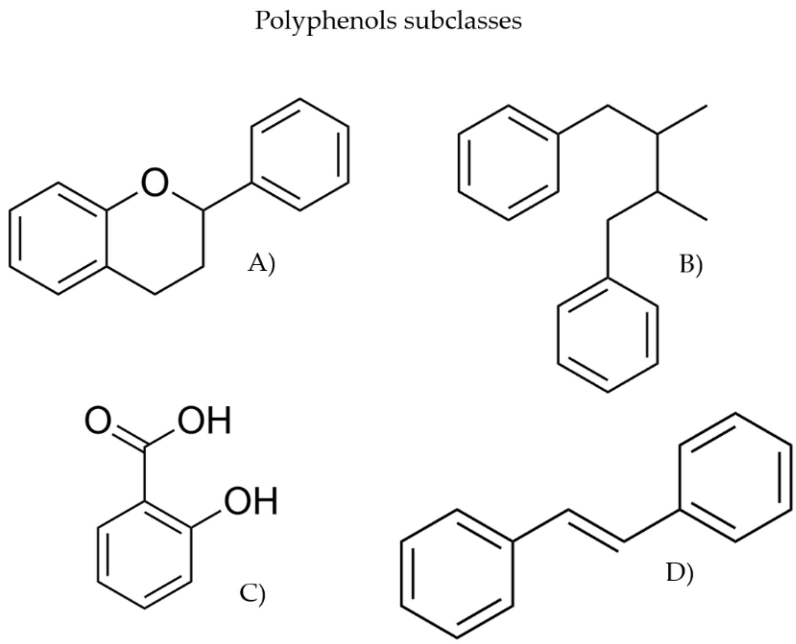

Figure 2. Representation of polyphenol subclasses structures (**A**) flavonoids, (**B**) lignans, (**C**) phenolic acids, and (**D**) stilbenes.

Flavonoids represent the most abundant and extensively investigated subclass of polyphenols and are widely distributed in fruits, vegetables, and various medicinal and aromatic plants [42,43]. Due to their nutritional, therapeutic, and antioxidant properties, flavonoids have broad applications across the food, pharmaceutical, chemical, and forest product industries [43]. Lignans are broadly documented in seeds, fruits, and vegetables [44]. These compounds display a wide range of biological activities, including anti-ageing, antimicrobial, hepatoprotective, cardioprotective, and other health-promoting effects [42]. Their diverse bioactivities have facilitated the incorporation of lignans into food formulations and various medical and clinical applications [45]. Phenolic acids, abundant in whole grains, coffee, and many plant-derived foods, are known for their antioxidant, anti-inflammatory, and antidiabetic functions [42]. Beyond their dietary relevance, phenolic acids play essential physiological and ecological roles in plants and exhibit therapeutic potential against a range of human diseases. Their redox properties enable them to act as reducing agents, hydrogen donors, and singlet oxygen quenchers [46]. Finally, the subclass of stilbenes, which includes the compound resveratrol, has attracted considerable attention due to its potential in preventing cardiovascular, oncological, and neurodegenerative disorders [42]. Naturally occurring stilbenes are widespread in plants, where they often function as phytoalexins produced in response to biotic and abiotic stresses. These compounds exhibit a broad spectrum of biological activities, as antimicrobial, antioxidant, anti-inflammatory, anti-leukemic, anti-platelet, anti-cancer, and anti-HIV effects. Due to their diverse pharmacological properties and structural complexity, stilbenes and their derivatives remain a focus of product research [47].

3. Mechanisms of Action of Plant-Derived Bioactive Compounds

The biological effects of plant-derived bioactive compounds are underpinned by multi-target molecular actions that converge on a limited set of conserved regulatory pathways involved in oxidative stress control, inflammatory signalling, and metabolic homeostasis, ultimately influencing processes linked to ageing and chronic disease progression. Rather than behaving as single-target drugs, many phytochemicals exert pleiotropic effects through complementary mechanisms, which helps explain their broad physiological relevance across complex biological systems [48–50].

3.1. Conserved Molecular and Cellular Pathways

A central feature of plant-derived bioactive compounds is their capacity to modulate oxidative stress and inflammatory signalling, two fundamental processes underlying ageing, metabolic dysfunction, and chronic disease progression. Many plant bioactives influence intracellular redox homeostasis not only through direct scavenging of reactive oxygen species but also by enhancing endogenous antioxidant defences and regulating redox-sensitive signalling cascades [48–50].

Key pathways recurrently modulated by these compounds include NF-κB and MAPK signalling, which coordinate inflammatory transcriptional programmes, and Nrf2-associated cytoprotective responses, which govern antioxidant and detoxification systems. Through these mechanisms, plant-derived bioactives attenuate chronic low-grade inflammation and promote cellular resilience [50–53].

In parallel, several compounds interact with metabolic sensing pathways, notably AMPK and SIRT1, contributing to improved mitochondrial function, energy balance and metabolic flexibility. These effects link redox and inflammatory control with metabolic adaptation and stress tolerance, reinforcing the view that plant bioactives act as multifunctional regulators rather than simple antioxidants [50,54,55].

An additional mechanistic layer involves microbiota-mediated effects. By shaping microbial community composition and stimulating the production of short-chain fatty acids, plant-derived bioactives indirectly modulate immune responses, epithelial barrier integrity and systemic metabolism. Together, these overlapping pathways illustrate how a limited set of conserved molecular hubs underpins the diverse biological actions of plant-derived compounds [56–58].

3.2. Structure–Mechanism Relationships in Plant-Derived Bioactive Compounds

The convergence of plant-derived bioactive compounds on conserved signalling hubs is closely linked to their chemical architecture and functional groups. Despite marked structural diversity, distinct phytochemical scaffolds repeatedly map onto similar molecular pathways, explaining their consistent biological relevance across different contexts [16,29].

Polyphenolic scaffolds, characterised by hydroxyl-rich aromatic systems, are particularly associated with modulation of redox-sensitive and inflammatory pathways. Structural features such as catechol or polyhydroxylated moieties favour interactions with transcription factors and kinases involved in NF-κB, MAPK, and Nrf2 signalling, while also supporting antioxidant capacity. More rigid and planar architectures, as observed in stilbene-type scaffolds, further enable interactions with metabolic sensing pathways, particularly those centred on AMPK and SIRT1, linking redox control to metabolic regulation [48,50,55,59].

Curcuminoid-type structures represent a distinct yet mechanistically convergent example. Their conjugated systems and phenolic functionalities allow simultaneous engagement with multiple inflammatory and oxidative stress pathways, including NF-κB-, MAPK-, and COX-2-related signalling, together with antioxidant enzyme induction. This multi-node interaction profile provides a structural rationale for their broad regulatory capacity [60–62].

In contrast, phenolic monoterpenes are characterised by higher lipophilicity and preferential interaction with biological membranes. Their mechanisms of action are dominated by membrane perturbation and modulation of microbial viability, while still intersecting inflammatory signalling pathways. This membrane–microbiota interface distinguishes their functional profile from that of polyphenolic compounds and underlies their relevance in contexts where microbial pressure and barrier integrity are critical [63–65].

Overall, these structure–mechanism relationships demonstrate how chemically diverse plant-derived bioactive compounds converge on a restricted set of conserved molecular hubs, generating functionally coherent biological effects [16,50].

3.3. From Molecular Mechanisms to One Health Effects

The evolutionary conservation of key signalling pathways provides the mechanistic foundation for the One Health relevance of plant-derived bioactive compounds. Pathways such as NF-κB, MAPKs, Nrf2, and AMPK/SIRT1 are conserved across taxa and play central roles in inflammation, metabolism, stress responses, and barrier function. Modulation at this level therefore leads to convergent physiological effects across species, despite differences in exposure routes, life stages, and biological systems [29,50,66].

Importantly, the environmental dimension emerges primarily as a system-level consequence of these shared mechanisms. By enhancing resilience, supporting metabolic and immune balance, and stabilising host–microbiota interactions, plant-derived bioactives can indirectly reduce reliance on antimicrobial and chemical interventions in medical, veterinary, and agricultural settings. This reduction in chemical pressure has downstream implications for environmental contamination, ecosystem stability, and antimicrobial resistance dynamics [67–69].

Taken together, plant-derived bioactive compounds should be viewed as multifunctional modulators of conserved biological systems, rather than single-target agents. Their structure–mechanism relationships explain why chemically diverse phytochemicals repeatedly align with integrated benefits across human, animal, and environmental health, providing a coherent mechanistic framework for the One Health relevance explored in the following section [16,50,66].

Table 1 summarises the main structural architectures of plant-derived bioactive compounds and their convergence on conserved molecular hubs, highlighting how chemically distinct scaffolds can generate coherent biological effects that underpin their One Health relevance.

Table 1. Main classes of plant-derived bioactive compounds, representative molecules, and key mechanisms of action relevant to human health.

Class of Plant-Derived Bioactive Compounds	Representative Molecules	Main Mechanisms of Action	References
Polyphenols	Quercetin, resveratrol, catechins, olive oil, and wine polyphenols	Scavenging of reactive oxygen species; modulation of NF-κB, MAPK, and Nrf2 pathways; improvement of endothelial function and mitochondrial activity	[24,25,48,51]
Flavonoids	Apigenin, luteolin, hesperidin, anthocyanins	Antioxidant and anti-inflammatory activity; regulation of cytokine production; modulation of immune and metabolic signalling	[49,50,54,59]
Phenolic acids	Apigenin, luteolin, hesperidin, anthocyanins	Antioxidant and anti-inflammatory activity; regulation of cytokine production; modulation of immune and metabolic signalling	[49,52,70,71]
Terpenoids and essential oil constituents	Caffeic, chlorogenic, and rosmarinic acids	Reduction in oxidative stress and inflammation; modulation of insulin resistance and glucose metabolism	[72–74]
Carotenoids	Caffeic, chlorogenic, and rosmarinic acids	Reduction in oxidative stress and inflammation; modulation of insulin resistance and glucose metabolism	[75–77]

4. One Health Relevance of Bioactive Compounds

4.1. Plant-Derived Bioactive Compounds and Human Health

In the context of human health, plant-derived bioactive compounds represent a chemically diverse group of secondary metabolites that have evolved through long-term ecological interactions between plants and their environment. This evolutionary pressure has resulted in molecules with multifunctional biological activities, capable of interacting with multiple molecular targets simultaneously. Such chemical diversity underpins their long-standing relevance in drug discovery and explains their renewed importance in modern preventive and personalised medicine [24,25].

Within the One Health framework, plant-derived bioactive compounds occupy a strategic position at the interface between nutrition, health and environmental sustainability. At dietary or nutraceutical levels, these compounds exert protective effects against oxidative stress, chronic inflammation, and metabolic dysregulation, processes that are central to the development of non-communicable diseases and shared across human, animal, and environmental health systems. Importantly, these effects gain additional relevance considering the widespread use of antibiotics, which, while essential in clinical and veterinary contexts, can disrupt host-associated microbiota and contribute to metabolic imbalance, immune dysregulation, and antimicrobial resistance across interconnected human, animal, and environmental compartments [56,67,78]. Their pleiotropic mechanisms distinguish them from single-target synthetic molecules, supporting holistic health maintenance rather than isolated therapeutic outcomes [79]. These effects are consistent with the conserved molecular mechanisms described in Section 3.

This section focuses specifically on bioactive compounds of plant origin, with particular emphasis on polyphenols, flavonoids, phenolic acids, terpenoids, and plant-derived polysaccharides, which represent the most extensively studied and biologically relevant classes in human health [80].

4.1.1. Impact of Plant-Derived Bioactive Compounds on Human Health

Through their integrated mechanisms of action, plant-derived bioactive compounds contribute to the prevention and modulation of multiple chronic conditions across the human lifespan, as also highlighted in recent lifespan-oriented reviews of polyphenol functionality [50,81].

4.1.2. Cardiovascular and Metabolic Health

Dietary polyphenols have been consistently associated with improved endothelial function, reduced oxidative damage, and modulation of vascular inflammation. These effects translate into lower blood pressure, improved lipid profiles, and reduced cardiovascular risk [51,82,83]. In metabolic disorders, including type 2 diabetes, plant-derived polyphenols and phenolic acids improve insulin sensitivity, regulate glucose uptake, and modulate the AGE–RAGE axis, contributing to better glycaemic control and metabolic stability [52,84].

4.1.3. Obesity and Low-Grade Inflammation

Plant-derived bioactive compounds play a relevant role in obesity-related metabolic inflammation by suppressing adipogenesis, regulating lipid metabolism, and modulating gut microbiota composition [54,60]. Prebiotic polysaccharides and polyphenols enhance microbial diversity and short-chain fatty acid production, thereby reducing systemic inflammation and supporting weight management strategies [54,85–87].

https://doi.org/10.3390/app16010327

4.1.4. Cancer Prevention and Cellular Protection

Several plant bioactive compounds, including flavonoids, stilbenes, and phenolic acids, exhibit chemopreventive properties by regulating oxidative stress, apoptosis, angiogenesis, and inflammatory signalling [88,89]. Their multitarget actions complement conventional therapies and contribute to reduced carcinogenic risk and improved cellular homeostasis [89,90].

4.1.5. Ageing, Cognitive Function, and Skin Health

Across the lifespan, plant-derived bioactive compounds support healthy ageing by modulating hallmarks of ageing such as oxidative stress, mitochondrial dysfunction, and chronic inflammation [81,91]. Polyphenols and carotenoids have been shown to improve cognitive performance, preserve skin integrity, and enhance stress resistance through pathways involving SIRT1, AMPK, and autophagy regulation [50,91,92]. These effects align with the emerging concept of nutritional strategies aimed at extending health span rather than lifespan alone. The major health outcomes associated with plant-derived bioactive compounds and their underlying biological mechanisms are synthesised in Table 2.

Table 2. Health outcomes associated with plant-derived bioactive compounds and their underlying biological mechanisms.

Health Domain	Main Bioactive Compounds Involved	Key Biological Mechanisms	Reported Health Outcomes	References
Cardiovascular health	Polyphenols, flavonoids	Reduction in oxidative stress; improvement of endothelial function; inhibition of vascular inflammation and platelet aggregation	Lower blood pressure; improved lipid profile; reduced cardiovascular risk	[51,76,82,93,94]
Type 2 diabetes and glycaemic control	Polyphenols, phenolic acids, flavonoids	Enhancement of insulin sensitivity; modulation of glucose metabolism; regulation of AGE–RAGE axis; microbiota-mediated effects	Improved glycaemic control and metabolic balance	[52,71,84,95]
Obesity and metabolic inflammation	Polyphenols, prebiotic fibres	Regulation of adipogenesis and lipid metabolism; modulation of gut microbiota; increased SCFA production	Reduced low-grade inflammation; support of weight management	[54,60,85–87]
Cancer prevention	Flavonoids, stilbenes, phenolic acids	Modulation of apoptosis, angiogenesis and inflammatory signalling; antioxidant protection	Chemopreventive effects; improved cellular homeostasis	[88–90,96]
Ageing, cognitive function and skin health	Polyphenols, carotenoids, anthocyanins	Regulation of oxidative stress, mitochondrial function and autophagy; activation of SIRT1 and AMPK pathways	Slowed functional decline; improved cognitive performance; enhanced skin integrity	[50,77,81,91,92,97,98]

4.2. Plant-Derived Bioactive Compounds and Animal Health

The progressive restriction of antibiotic growth promoters (AGPs) in livestock production has intensified the search for effective and sustainable alternatives that maintain animal health, productivity, and welfare while reducing selective pressure for antimicrobial resistance (AMR) [67,68]. Within this context, plant-derived bioactive compounds have emerged as promising nutritional and functional tools, aligned with the One Health framework by simultaneously benefiting animal performance, food safety, and environmental protection [67,69].

Unlike conventional antibiotics, plant-derived bioactive compounds exert multifunctional effects that extend beyond pathogen suppression, including modulation of gut microbiota, enhancement of intestinal barrier integrity, and regulation of immune responses. These properties make them particularly attractive for integration into antibiotic-free production systems [67,99].

4.2.1. Plant-Derived Bioactive Compounds as Alternatives to Antibiotics

A wide range of plant-derived bioactive compounds, including polyphenols, essential oil constituents and tannin-rich extracts, have been evaluated as alternatives to AGPs in in vivo livestock models. Supplementation with compounds such as thymol, carvacrol, eugenol, and quercetin has been associated with improved growth performance, feed conversion efficiency, and reduced intestinal colonisation by pathogenic bacteria in poultry and swine [67,68].

These effects are supported by in vitro evidence demonstrating antimicrobial activity against enteric pathogens and interference with quorum sensing and biofilm formation [100,101]. However, the relevance of these compounds lies primarily in their in vivo efficacy, where multi-target mechanisms contribute to stable and resilient gut ecosystems rather than indiscriminate microbial suppression [67,68].

In aquaculture, plant-derived bioactive compounds have similarly shown beneficial effects, including improved antioxidant status, enhanced innate immunity, and reduced disease-related mortality in fish species, reinforcing their applicability across diverse animal production systems [99,102].

Despite these advantages, variability in chemical composition, dose optimisation, and stability during feed processing remain challenges for large-scale application. Advances in encapsulation and formulation strategies are increasingly addressing these limitations, improving bioavailability and consistency of biological effects [69,103].

4.2.2. Modulation of Gut Health, Microbiota, and Immune Function

The gastrointestinal tract represents a critical interface between diet, microbiota, and host immunity, making it a primary target for plant-derived bioactive compounds [56,78]. In vivo studies in poultry and swine have demonstrated that supplementation with phytogenic compounds and plant extracts enhances villus height, tight-junction protein expression, and mucosal integrity, thereby strengthening the intestinal barrier [99,104].

Concomitantly, these compounds modulate gut microbial communities by promoting beneficial taxa such as Lactobacillus and Bifidobacterium while suppressing opportunistic pathogens. These shifts are associated with reduced intestinal inflammation, improved nutrient absorption and increased production of short-chain fatty acids, which play a central role in immune regulation [57,99].

Plant-derived bioactive compounds also exert immunomodulatory effects by attenuating pro-inflammatory cytokines (e.g., TNF-α, IL-6) and enhancing anti-inflammatory mediators such as IL-10. Such immune balancing contributes to increased resilience against enteric infections and may reduce the need for therapeutic antibiotic interventions [67,99,105].

Synergistic strategies combining plant-derived compounds with probiotics or antimicrobial peptides have shown enhanced efficacy in in vivo animal models, highlighting the potential of integrated nutritional approaches to support gut health and immune competence [106,107].

4.2.3. Implications for Zoonotic Risk and Antimicrobial Resistance

Beyond individual animal health, the use of plant-derived bioactive compounds has broader implications for zoonotic disease control and antimicrobial resistance (AMR) mitigation. By reducing pathogen load, intestinal dysbiosis and environmental shedding of resistant bacteria, these compounds contribute to lower transmission risks along the food chain [67,108].

Recent surveillance studies have revealed a high prevalence of AMR genes in livestock-associated environments, emphasising the urgency of alternative strategies that reduce antibiotic dependence [109]. Plant-derived bioactive compounds, together with prebiotics, probiotics, and antimicrobial peptides, can mitigate these reservoirs by promoting stable microbial ecosystems and enhancing host defences [107,110].

However, effective implementation requires harmonised regulatory frameworks, standardised dosing strategies, and comprehensive risk assessments to ensure safety and reproducibility. When integrated into antibiotic-free production systems, plant-derived bioactive compounds represent a viable pathway toward reducing AMR dissemination while maintaining animal productivity and welfare within a One Health perspective [69,108].

Representative examples of plant-derived bioactive compounds evaluated in livestock production systems, together with their main in vivo effects and relevance within the One Health framework, are summarised in Table 3.

Table 3. Representative plant-derived bioactive compounds evaluated in livestock and aquaculture systems and their relevance within the One Health framework.

Plant-Derived Bioactive Compounds	Animal Model (In Vivo)	Main Observed Effects	Relevance Within the One Health Framework	References
Essential oil constituents (thymol, carvacrol, eugenol)	Poultry, swine	Reduced intestinal colonisation by pathogenic bacteria; improved feed conversion ratio; modulation of gut microbiota	Reduced use of antibiotic growth promoters; lower selective pressure for AMR	[67,68]
Plant polyphenols (e.g., quercetin, resveratrol)	Poultry, piglets, fish	Improved antioxidant status; enhanced gut integrity; modulation of immune responses	Improved animal resilience reduces therapeutic antibiotic interventions	[68,111]
Tannin-rich plant extracts	Ruminants, poultry	Reduced enteric pathogens; improved nitrogen utilisation; modulation of rumen microbiota	Lower environmental contamination and reduced antimicrobial inputs	[68,111]
Plant-derived prebiotics (dietary fibres, polysaccharides)	Poultry, swine	Increased beneficial gut bacteria; enhanced short-chain fatty acid production; improved intestinal barrier function	Improved gut health contributes to reduced zoonotic risk	[99,106]
Phytogenic blends (plant extracts; essential oils)	Poultry, swine	Improved growth performance; reduced intestinal inflammation; enhanced immune competence	Supports antibiotic-free production systems	[67,69]

Table 3. *Cont.*

Plant-Derived Bioactive Compounds	Animal Model (In Vivo)	Main Observed Effects	Relevance Within the One Health Framework	References
Plant-derived bioactives combined with probiotics or antimicrobial peptides	Poultry, piglets	Synergistic improvement of gut microbiota stability and immune balance	Integrated strategies reduce AMR dissemination along the food chain	[106,112]
Plant-derived bioactives in aquaculture feeds	Fish	Enhanced innate immunity; reduced disease-related mortality; improved redox balance	Reduced antimicrobial use in aquatic environments	[111]

4.3. Environmental Health and Ecosystem Sustainability

Plant-derived bioactive compounds play a fundamental role in environmental health by mediating ecological interactions, supporting sustainable agricultural practices and reducing reliance on synthetic chemical inputs [67,103]. Within the One Health framework, their environmental relevance lies not only in their biological activity but also in their generally lower environmental persistence, reduced ecotoxicity and potential contribution to biodiversity preservation and antimicrobial resistance (AMR) mitigation [103,113].

Unlike conventional agrochemicals, many plant-derived bioactives are biodegradable and act through multitarget mechanisms, which limits the development of resistance and minimises unintended impacts on non-target organisms. These properties position them as key components of environmentally responsible strategies in agriculture and ecosystem management [103,112].

4.3.1. Role of Plant-Derived Bioactive Compounds in Ecological Interactions

In natural ecosystems, plant-derived bioactive compounds such as phenolics, terpenoids, alkaloids, and peptides act as chemical mediators regulating plant–microbe, microbe–microbe, and plant–insect interactions. These compounds contribute to plant defence against pathogens and herbivores, modulate microbial competition in the rhizosphere, and enhance tolerance to abiotic stressors, including drought, ultraviolet radiation, and heavy metals [29,30,35].

Root-exuded phenolic acids and other secondary metabolites can selectively stimulate beneficial rhizobacteria, promoting nutrient acquisition and plant growth while suppressing phytopathogens. In parallel, microbial metabolites influenced by plant-derived substrates contribute to soil aggregation, carbon sequestration, and nutrient cycling, reinforcing ecosystem stability [35,114,115].

Importantly, these ecological functions are closely linked to environmental health outcomes, as they support resilient soil microbiomes and reduce the need for synthetic inputs that disrupt ecological balance.

4.3.2. Applications in Biopesticides, Biofertilisers, and Sustainable Agriculture

The multifunctionality of plant-derived bioactive compounds has driven their application in biopesticides, biofertilisers, and biostimulants as sustainable alternatives to conventional agrochemicals. Well-established examples include azadirachtin from Azadirachta indica and pyrethrins from Chrysanthemum species, which exhibit effective insecticidal activity while displaying lower toxicity towards non-target organisms when properly applied [111,112].

Plant-derived compounds are also increasingly incorporated into integrated pest management strategies, often in combination with microbial agents. Such approaches enhance pest control efficacy while reducing environmental contamination and selective pressure for resistance development [103,112]. In parallel, humic substances and seaweed-derived polysaccharides act as biostimulants, improving root development, nutrient uptake, and soil microbial activity, thereby supporting sustainable crop productivity [114,115].

These applications demonstrate that plant-derived bioactive compounds contribute not only to pest suppression but also to broader ecosystem services, including soil health preservation and biodiversity enhancement, as summarised in Table 4.

Table 4. Representative plant-derived bioactive compounds and related natural products with ecological functions and applications in sustainable agriculture within a One Health framework.

Compound/Source	Main Ecological Function	Botanical Biopesticide	One Health Relevance	References
Azadirachtin (*Azadirachta indica*)	Insect growth regulation	Botanical biopesticide	Reduced reliance on synthetic pesticides; protection of non-target species	[69,99,103,111,112,114]
Pyrethrins (*Chrysanthemum* spp.)	Neurotoxic to insect pests	Biopesticide in integrated pest management	Lower environmental persistence and toxicity	[69,103,111,114]
Phenolic acids (root exudates)	Plant defence and microbial signalling	Rhizosphere modulation	Enhanced soil microbial balance	[67–69,99,103,104,106–112,115]
Humic and fulvic acids	Soil conditioning and nutrient cycling	Biofertilisers and soil amendments	Improved soil health and crop resilience	[69,99,103,104,106–108,110–118]
Seaweed-derived polysaccharides	Biostimulation	Improved root growth and nutrient uptake	Sustainable crop productivity	[114]

4.3.3. Reduction in Environmental Impact and Contribution to One Health

Replacing or reducing synthetic agrochemicals with plant-derived bioactive compounds offers tangible environmental benefits. Conventional pesticides and fertilisers are often persistent, bioaccumulative, and harmful to pollinators, aquatic organisms, and soil microbiota, contributing to long-term ecosystem degradation [103,111]. Figure 3 illustrates the environmental pathways of plant-derived bioactive compounds, from their natural sources to agricultural application and ecosystem-level effects, highlighting their contribution to environmental sustainability and the One Health framework.

In contrast, plant-derived bioactive compounds generally exhibit faster environmental degradation and lower ecotoxicological profiles, reducing unintended impacts on non-target species and limiting contamination of water and soil systems [103,112]. Life cycle and risk assessment studies further indicate that biologically based inputs can reduce chemical residues and environmental pressure when integrated into sustainable agricultural practices [112].

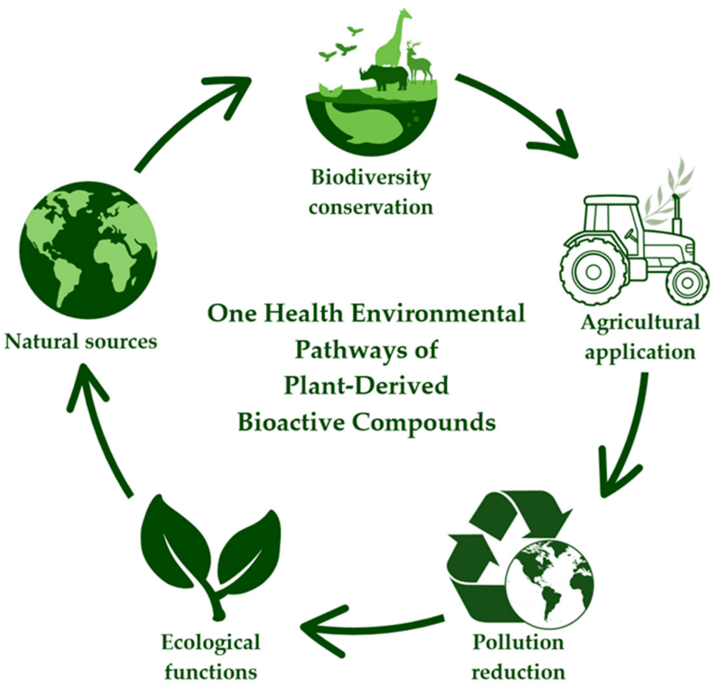

Figure 3. Environmental pathways of plant-derived bioactive compounds within a One Health framework, illustrating their progression from plant-based natural sources to agricultural applications, pollution reduction, ecological functions, and biodiversity conservation, with integrated implications for human, animal, and environmental health.

From a One Health perspective, these environmental benefits have direct implications for human and animal health. Reduced chemical loads in ecosystems lower exposure risks across the food chain and indirectly contribute to limiting the environmental dissemination of antimicrobial-resistant bacteria. By supporting biodiversity, soil resilience, and ecological balance, plant-derived bioactive compounds represent a validated strategy for promoting environmental sustainability within integrated health frameworks [67,108,109].

Key environmental benefits and One Health implications associated with the use of plant-derived bioactive compounds, in comparison with conventional synthetic inputs, are summarised in Table 5.

Table 5. Environmental and One Health implications of plant-derived bioactive compounds compared with conventional synthetic agrochemicals.

Aspect	Plant-Derived Bioactive Compounds	Conventional Synthetic Inputs	One Health Implications	References
Environmental persistence	Generally biodegradable with shorter environmental half-life	Often persistent and bioaccumulative	Reduced long-term soil and water contamination	[103,116]
Ecotoxicity to non-target organisms	Lower toxicity when properly applied; reduced impact on pollinators and aquatic life	High toxicity reported for pollinators, soil fauna and aquatic organisms	Protection of ecosystem services and biodiversity	[103,111]

Table 5. *Cont.*

Aspect	Plant-Derived Bioactive Compounds	Conventional Synthetic Inputs	One Health Implications	References
Resistance development	Multitarget modes of action reduce resistance pressure	Single-target mechanisms favour resistance emergence	Lower risk of resistance spread across ecosystems	[112,116]
Impact on soil microbiota	Supports microbial diversity and functional resilience	Disrupts soil microbial communities	Enhanced soil health and nutrient cycling	[111,115]
Contribution to AMR dissemination	Indirect reduction through lower chemical and antimicrobial pressure	Promotes co-selection of resistance traits	Reduced environmental AMR reservoirs	[108,113,117]
Alignment with sustainability frameworks	Compatible with circular economy and integrated pest management	Often incompatible with long-term sustainability goals	Supports One Health and Sustainable Development Goals	[112,116]

Figure 4 synthesises the One Health framework discussed in this section, illustrating how chemically distinct plant-derived bioactive compounds converge on conserved molecular hubs (e.g., NF-κB/MAPKs, Nrf2-related cytoprotection, and AMPK/SIRT1-linked metabolic sensing). Modulation at the pathway level translates into coordinated cellular and organism-level effects in human and animal systems, with indirect environmental benefits arising from reduced chemical and antimicrobial pressure.

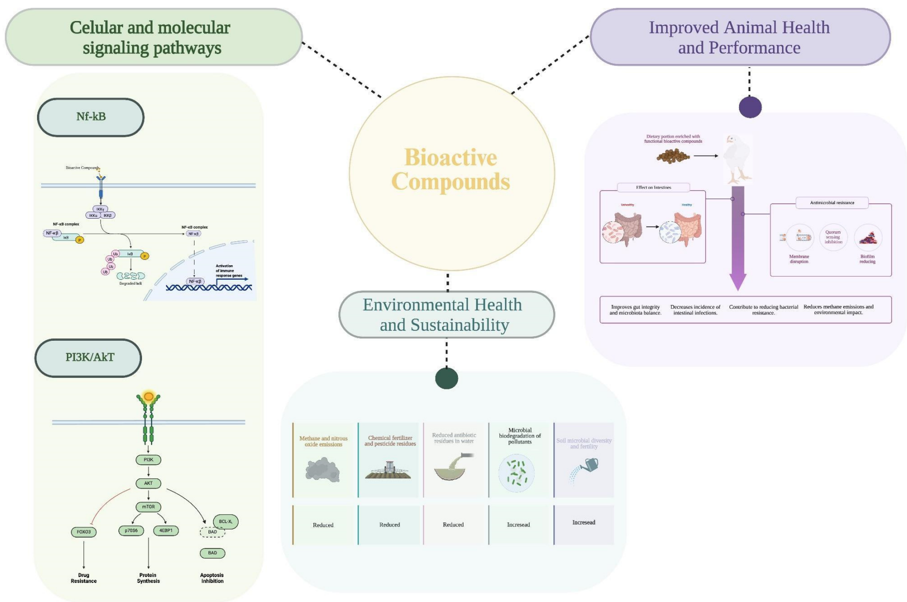

Figure 4. Overview of the main effects of bioactive compounds across cellular, animal, and environmental levels, illustrating their integrative contribution to the One Health concept.

5. Applicability of Selected Plant-Derived Bioactive Compounds: Evidence-Based Case Examples Within One Health

Building on the mechanistic framework outlined in Sections 3 and 4, Table 6 compiles representative case examples showing how selected plant-derived bioactive compounds translate conserved pathway modulation into cross-pillar outcomes. Quercetin, resveratrol, curcumin, thymol, carvacrol, and rosmarinic acid exemplify an upstream (“preventive”) intervention logic: by targeting signalling hubs such as NF-κB, MAPKs, and AMPK/SIRT1, they can attenuate inflammatory signalling and support redox homeostasis. Several also display antimicrobial activity and/or microbiota-modulatory effects, consistent with benefits that extend from host resilience to downstream environmental co-benefits via reduced antimicrobial and chemical pressure, as summarised in Figure 5.

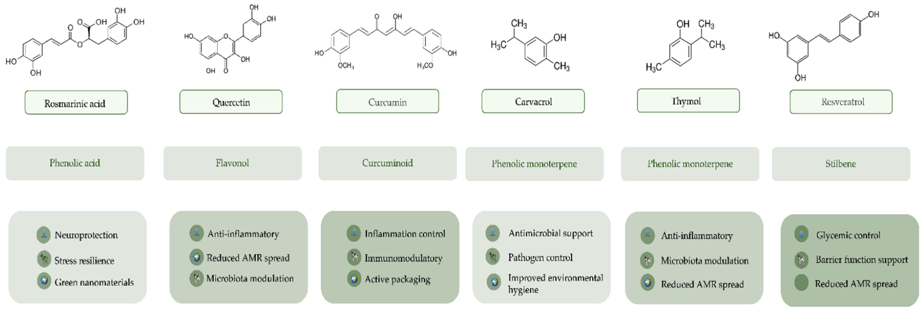

Figure 5. Graphical summary of the One Health-relevant bioactivities of six representative plant-derived bioactive compounds (quercetin, resveratrol, curcumin, rosmarinic acid, thymol, and carvacrol) across the human, animal, and environmental pillars.

5.1. Human Health

In the human health pillar, the applicability of these plant-derived bioactive compounds lies in their use as nutritional strategies and adjunct interventions in contexts characterised by chronic inflammation, oxidative stress, and metabolic dysfunction, as illustrated in Table 4. The compiled evidence supports their action on central regulatory mechanisms controlling inflammation and metabolism, notably via modulation of NF-κB, including inhibition of IκBα phosphorylation and the consequent reduction in NF-κB activation, as well as MAPKs and AMPK/SIRT1, resulting in decreased pro-inflammatory mediators and reinforcement of endogenous antioxidant responses. This mechanistic coherence is exemplified by quercetin, which is associated with anti-inflammatory effects in cardiometabolic settings through NF-κB-related regulation, and by resveratrol, whose action on SIRT1/AMPK and related metabolic signalling pathways is consistent with improvements in glycaemic homeostasis reported in Table 4 [53,119–122]. Complementarily, curcumin displays an integrative profile by modulating NF-κB/AMPK/COX-2 and inducing endogenous antioxidant enzymes (e.g., SOD, CAT, GPx), supporting its relevance in inflammatory and metabolic disorders. Importantly, these compounds may also be pertinent in situations where barrier integrity and mucosal immunoregulation shape clinical expression of inflammation: rosmarinic acid, for instance, is linked in Table 6 to improvements in allergic manifestations at the nasal mucosa level, consistent with modulation of NF-κB/MAPKs and related signalling (including PI3K/Akt). Overall, these examples indicate that applicability within the human pillar is not merely "antioxidant" or "anti-inflammatory" in generic terms but instead rests on defined, biologically grounded mechanisms with clinical relevance, supporting their integration into prevention and supportive therapeutic approaches aligned with the One Health paradigm.

5.2. Animal Health

In the animal health pillar, these compounds are applicable as functional feed and management additives capable of improving performance, health resilience, and product quality in key species, including poultry, swine, ruminants, and fish, as synthesised in Table 6. Their effects are biologically plausible because they involve modulation of conserved pathways governing inflammation, oxidative stress, and metabolism, including regulation of NF-κB and MAPKs, and, in some cases, activation of AMPK/SIRT1. A particularly relevant axis is the modulation of the gut microbiota and intestinal ecosystem, with direct implications for enteric health and infectious pressure. This is clearly illustrated by quercetin, which is associated with reduced burdens of undesirable microbes (e.g., total coliforms and Clostridium perfringens) alongside increased Lactobacillus spp. counts in broiler chickens (Table 6) [123]. Likewise, thymol is associated with increased Lactobacillus and reduced *E. coli* and *Clostridium* spp., whereas carvacrol is linked to reduced *Clostridium perfringens* and *Salmonella* spp. and to consistent zootechnical and health benefits across species (Table 6) [63,64,124]. In parallel, resveratrol stands out for improving intestinal morphology and barrier function and lowering inflammatory markers, while curcumin is highlighted for supporting host resilience under enteric challenge (e.g., reduced oocyst shedding) and for improving immunity-related and oxidative stability outcomes in poultry (Table 6) [102,125]. Taken together, these examples support their One Health applicability in animal production: promoting gut health, immunity, and pathogen control through alternatives compatible with reduced reliance on antibiotic growth promoters.

5.3. Environmental Health

Finally, within the environmental pillar, the applicability of these phytochemicals becomes evident when Table 6 is interpreted as a causal chain: improved animal health and reduced pathogen burdens can translate into lower pressure to use antibiotics, decreasing environmental discharge and the selective pressure that drives antimicrobial resistance (AMR). In this context, compounds such as quercetin, resveratrol, thymol, and carvacrol have strategic value because their documented effects on gut microbial load, host resilience, and performance support partial substitution of AGPs and contribute to reduced pharmaceutical residues entering manure, effluents, and receiving ecosystems, thereby benefiting soil and water quality and limiting AMR dissemination (Table 6). Beyond antibiotic-related externalities, Table 4 also links thymol and carvacrol to reductions in parameters relevant to the sustainability of livestock units, including odour, emissions such as ammonia, and in ruminant contexts methane, underscoring that their impact is not only sanitary but also associated with environmental footprint [124]. Finally, Table 6 highlights use cases that extend applicability into technological and mitigation solutions: curcumin is presented as relevant for biosensors and active packaging, and rosmarinic acid as a candidate for incorporation into green nanomaterials for pollutant removal [126,127]. These examples indicate that plant-derived bioactive compounds can reduce environmental chemical burdens not only through “less antibiotic use” but also through improved monitoring and contaminant mitigation strategies across the agri-food chain.

Overall, the evidence summarised in Table 6 supports the view that selected plant-derived bioactive compounds can be operationalised as One Health-compatible interventions, because they target conserved biological nodes, particularly inflammatory and redox-regulatory networks and host–microbe interactions, across humans and animals, while also offering pathways to reduce environmental externalities. In human health, their relevance is grounded in mechanistically defined modulation of inflammation and metabolism; in animal production, they provide functional tools to strengthen gut health and resilience and to reduce pathogen pressure, thereby supporting strategies that can lower reliance on antibiotic growth promoters. Importantly, these cross-sector effects translate into environmental relevance through reduced pharmaceutical residues, reduced selection pressure for antimicrobial resistance, and, for some compounds, lower emission-related burdens and applicability in greener technologies (e.g., active packaging, biosensing, or pollutant-removal materials). Future implementation should prioritise well-standardised formulations, improved bioavailability where needed, and harmonised outcome reporting to enable robust cross-species translation and real-world uptake within One Health policies.

Table 6. Evidence-based applicability of plant-derived bioactive compounds within One Health: structure, key pathways, and effects across humans, animals, and the environment.

Compound	Conformation	Pathway	Experimental Models	Human Health	Animal Health	Environmental Relevance	References
Quercetin	Flavonol ($C_{15}H_{10}O_7$) with five hydroxyls at positions 3, 5, 7, 3′, 4′.	Inhibition of IκBα phosphorylation and NF-κB activation.	Humans; Broiler chickens; Swine; Ruminants.	In coronary artery disease, oral supplementation (120 mg/day) reduced circulating IL-1β and TNF-α and downregulated IκBα expression.	In broiler chickens, dietary quercetin supplementation at 200–400 ppm for 35 days increased the European production efficiency factor (EPEF), decreased total coliforms and Clostridium perfringens, increased Lactobacillus counts, and improved antioxidant status, meat quality and overall productive performance.	Reduced need for AGPs; lower drug residues in products and effluents.	[119–121,123,128–131]
Resveratrol	Stilbene (3,5,4′-trihydroxystilbene) with two phenolic rings linked by an ethylenic bond.	Activation of SIRT1/AMPK; inhibition of PI3K/Akt/mTOR; modulation of ERK/JNK/p38 and Bcl-2/Bax-dependent apoptosis.	Humans; Broiler chickens; Swine; Ruminants; Fish.	In T2D (1 g/day for 45 days), improved insulin sensitivity and reduced fasting glucose.	In weaned piglets, dietary resveratrol at 300 mg/kg feed for 42 days improved growth, antioxidant status, intestinal morphology and barrier function and lowered inflammatory markers; in growing–finishing pigs, 300–600 mg/kg for 49 days enhanced meat quality and reduced carcass fat; in fish species such as tilapia, turbot and rainbow trout, inclusion of 0.05–0.3% of the diet for 9 weeks increased antioxidant capacity, disease resistance and flesh quality, although the highest doses could attenuate growth.	Substitution for AGPs reduces antibiotic discharge into ecosystems and mitigates AMR spread; lower methane improves environmental footprint.	[102,122,125,132–136]

Table 6. *Cont.*

Compound	Conformation	Pathway	Experimental Models	Human Health	Animal Health	Environmental Relevance	References
Curcumin	Curcuminoid (diferuloylmethane) with two phenolic rings linked by a conjugated β-diketone chain bearing hydroxyl and methoxy groups.	Modulation of NF-κB, AMPK and COX-2; induction in SOD, CAT, and GPx; inhibition of IκB kinase; regulation of p38/JNK in inflammation and apoptosis.	Humans; Broiler chickens; Swine.	In T2D and ulcerative colitis, oral supplementation (80 mg/day for 3 months) reduced HbA1c, fasting glucose and clinical disease activity.	In poultry, dietary curcumin supplementation at about 0.25–0.5% of the diet for 8 weeks reduced oocyst shedding (Eimeria), improved egg quality, decreased abdominal fat and enhanced immunity and oxidative stability of meat.	Supports replacement of pharmaceutical additives; applicable to biosensors and active packaging, reducing chemical burden in ecosystems.	[60,62,126,127,137–143]
Thymol	Monoterpenoid phenol (2-isopropyl-5-methylphenol) with an isopropyl and a para-hydroxyl group on the aromatic ring.	Modulation of NF-κB and COX-2 signalling.	Humans; Broiler chickens; Swine; Ruminants; Fish.	Antimicrobial against S. aureus, E. coli, Candida spp, anti-inflammatory effect (NF-κB, COX-2), antioxidant, potential in inflammatory disorders and cancer.	↑ Growth, ↓ Clostridium spp., improved meat/egg quality. ↑Lactobacillus, ↓ *E. coli*, better digestibility, ↑ survival, immunity, resistance to infections.	Reduced antibiotic residues in manure; ↓ coliforms, ammonia, methane and odour in livestock units.	[58–60,63,64,144]
Carvacrol	Monoterpenoid phenol, positional isomer of thymol (5-isopropyl-2-methylphenol) with an ortho-hydroxyl group.	Modulation of NF-κB and MAPKs.	Humans; Broiler chickens; Swine; Ruminants; fish.	Anti-inflammatory (↓ TNF-α, IL-6, IL-1β), antimicrobial against Gram± bacteria and Candida biofilms; neuroprotective and metabolically beneficial. In a phase I clinical study, healthy adults supplemented orally with 1–2 mg/kg/day of carvacrol for 30 days showed good safety and tolerability, with only mild laboratory changes remaining within normal reference ranges.	Dietary incorporation of carvacrol resulted in clear zootechnical and health benefits across species. In broilers, 200–500 mg/kg feed for 28–42 days increased growth and feed efficiency and reduced Clostridium perfringens and Salmonella spp; in weaned piglets, 100 mg/kg for 14 days reduced post-weaning diarrhoea; in laying hens, 300 mg/kg for ~50 weeks improved egg quality and antioxidant status; in fish, 1–3 g/kg in feed increased survival.	↓ Antibiotic reliance; ↓ pathogen shedding in litter and manure; ↓ odour and ammonia emissions; ↓ methane from ruminants; lower environmental pharmaceutical load.	[65,124,145,146]

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Table 6. *Cont.*

Compound	Conformation	Pathway	Experimental Models	Human Health	Animal Health	Environmental Relevance	References
Rosmarinic acid	Polyphenolic ester of caffeic acid and 3,4-dihydroxyphenyllactic acid, with two catechol moieties.	Modulation of NF-κB and MAPKs (ERK, JNK, p38); regulation of PI3K/Akt.	Humans; Broiler chickens; Rodents; Fish.	Anti-inflammatory and antioxidant; neuroprotective (Alzheimer'sParkinson's); improves glucose metabolism; hepatoprotective and anticancer. In patients with seasonal allergic rhinoconjunctivitis, oral rosmarinic acid at 50 or 200 mg/day for 21 days reduced nasal symptoms and neutrophil/eosinophil infiltration.	In rodent models, oral rosmarinic acid at 1–50 mg/kg/day for 12 days protected kidney, liver, heart and brain from toxic, ischaemic or diabetic injury by reducing oxidative stress, inflammation and apoptosis; in poultry and fish, diets enriched with rosmarinic-acid-rich extracts administered for several weeks improved antioxidant status, immune responses and survival under infectious challenge.	Used in green nanomaterials for pollutant removal; enables partial replacement of synthetic additives and reduces pharmaceutical residues in ecosystems.	[147–149]

6. Challenges and Future Perspectives

Plant-derived bioactive compounds, with applications in medicine, agriculture, and direct impact on environmental sustainability, display several bioactive properties, including antimicrobial, antioxidant, anti-inflammatory, and antifungal effects, making them interesting alternatives to synthetic chemicals [150,151]. However, scientific, technological, and regulatory challenges remain, as comprehensive safety assessments, toxicological evaluations, and scientific validation of health claims are necessary and often supported by clinical trials and analytical verification [152]. Additionally, it is essential to achieve consistent bioavailability, stability, and standardisation, as variations in natural sources can lead to differences in chemical composition and biological activity. The same compounds may exhibit low solubility, limited absorption, and rapid degradation, thereby reducing their clinical or functional efficacy [153]. Ensuring standardisation and reproducibility during extraction and formulation is essential for consistent biological performance and product quality [154]. Advances in omics technologies, genomics, proteomics, and metabolomics are transforming the discovery and analysis of bioactive compounds. These high-throughput methods enable detailed characterisation of biological systems, allowing rapid and accurate identification of biosynthetic gene clusters, metabolic pathways, and bioactive metabolites. The combination of omics data with computational tools, such as bioinformatics and artificial intelligence (AI), accelerates the discovery of new bioactive compounds, supporting targeted biotechnological innovations and personalised applications in health and agriculture [66,155]. Looking forward, with an emphasis on the One Health approach, research should focus on developing cost-effective, scalable, and energy-efficient extraction methods. Collaboration between academia and industry is crucial to integrate advances in extraction methods with functional validation and product development. Furthermore, improving regulatory clarity and harmonisation worldwide can drive innovation while ensuring safety and transparency through accurate labelling and traceability.

7. Conclusions

This review highlights the vital roles in promoting the One Health strategy that plant-derived bioactive compounds play. For human health, these natural bioactive compounds are important as preventive and therapeutic agents by modulating oxidative stress, inflammation, and infection pathways, offering potential alternatives to synthetic drugs for managing chronic diseases and enhancing immune function. Regarding animal health, it might serve as a sustainable substitute for antibiotics and synthetic additives, improving gut health, boosting immunity, and helping mitigate AMR. If we think from an environmental perspective, bioactive compounds contribute to ecological balance by functioning as natural defence mechanisms against predators, pathogens, and stressors, while their application in biopesticides, biofertilisers, and soil enhancers supports sustainable agriculture and biodiversity conservation. Their biodegradability and low toxicity further reduce environmental impact compared to conventional chemicals.

To conclude, it is imperative to overcome the scientific, technological, and regulatory challenges to unlock the full potential of plant-derived bioactive compounds. Through sustainable extraction strategies, rigorous standardization, and collaborative innovation, bioactive compounds obtained from plant-derived products can form the foundation of nutraceutical alternatives, supporting both human health and environmental sustainability, and making them essential to integrated One Health strategies that link human, animal, and ecosystem well-being.

https://doi.org/10.3390/app16010327

Author Contributions: Conceptualization, A.C.G., A.R.P., A.C., E.O.-F., and J.C.L.M.; methodology, A.C.G., A.R.P., A.C., E.O.-F., and J.C.L.M.; software, A.C.G., A.R.P., A.C., E.O.-F., and J.C.L.M.; validation, A.C.G., A.R.P., A.C., E.O.-F., and J.C.L.M.; formal analysis, A.C.G., A.R.P., A.C., E.O.-F., and J.C.L.M.; investigation, A.C.G., A.R.P., A.C., E.O.-F., and J.C.L.M.; resources, A.C.G., A.R.P., A.C., E.O.-F., and J.C.L.M.; data curation, A.C.G., A.R.P., A.C., E.O.-F., and J.C.L.M.; writing—original draft preparation, A.C.G., A.R.P., A.C., E.O.-F., and J.C.L.M.; writing—review and editing, J.G., A.L., M.J.S., M.M.P., and M.J.A., visualization, J.G., A.L., M.J.S., M.M.P., and M.J.A.; supervision, J.G., A.L., M.J.S., M.M.P., and M.J.A.; project administration, M.J.S., M.M.P., and M.J.A.; funding acquisition, M.J.S., M.M.P., and M.J.A. All authors have read and agreed to the published version of the manuscript.

Funding: This work is supported by National Funds by FCT–Portuguese Foundation for Science and Technology, under the projects FCT/MCTES (PIDDAC): CIMO, UIDB/00690/2020 (https://doi.org/10.54499/UIDB/00690/2020) and UIDP/00690/2020 (https://doi.org/10.54499/UIDP/00690/2020); SusTEC, LA/P/0007/2020 (https://doi.org/10.54499/LA/P/0007/2020) Portugal; CECAV UIDB/00772/2020 (https://doi.org/10.54499/UIDB/00772/2020), CITAB, UID/04033/2025 and LA/P/0126/2020 (https://doi.org/10.54499/LA/P/0126/2020), LiveWell, UID/6157/2025, and CBQF, UID/50016/2025.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The raw data supporting the conclusions of this article will be made available by the authors on request.

Acknowledgments: Juliana Garcia and André Lemos acknowledge funding support from Portuguese public funding through Investimento RE-C05-i02–Missão Interface N.° 01/C05-i02/2022. Ana Rita Pinto would like to acknowledge FCT–Fundação para a Ciência e Tecnologia, I.P. for the support and individual grant (2024.06170.BDANA). André Cima would like to acknowledge FCT–Fundação para a Ciência e a Tecnologia, I.P. for the support and individual grant (PRT/BD/154693/2023, https://doi.org/10.54499/PRT/BD/154693/2023) under the protocol "Centro para a Valorização do Barroso–Património Agrícola Mundial–Valor Barroso". Joana Martins would like to acknowledge FCT–Fundação para a Ciência e Tecnologia, I.P. for the support and individual grant (2023.05610.BDANA, https://doi.org/10.54499/2023.05610.BDANA). Eva Olo-Fontinha would like to acknowledge FCT–Fundação para a Ciência e Tecnologia, I.P. for the support and individual grant 2024.06281.BDANA.

Conflicts of Interest: The authors declare no conflicts of interest.

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