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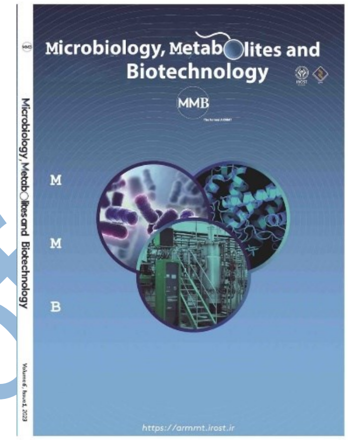
Biotechnological Applications of Selected Plant Species in Iraqi Kurdistan



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Biotechnological Applications of Selected Plant Species in Iraqi Kurdistan

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Abstract

There is a wide variety of plant species native to the Kurdistan region that could serve as a rich source of valuable bioactive metabolites. These metabolites have been utilized globally in various environmental and industrial fields, including pharmaceuticals, insecticides, agriculture, skin care products, environmental clean-up, and food preservation applications, giving sustainable and eco-friendly substitute to synthetic chemicals. Additionally, they contribute significantly to enhancing product quality, industrial and medical development, aiding in preservation and increasing the shelf life of natural products. While the commercial value of these metabolites is expanding in the global market, they have not been adequately utilized and researched in the Kurdistan region. This review tries to fill the research gap by precisely detailing 21 different plant species, phytochemical constituents, and potential applications in various fields. A broad literature survey was conducted to identify prominent plant species of industrial and environmental importance, and their investigated bioactive compounds are summarized to provide a comprehensive reference for future studies. Additionally, this article discusses the potential of introducing Kurdistan's phytochemicals to the world of sustainable development and global bioeconomy. Through the correlation of the broad application of these metabolites with the scientific research in the region, Kurdistan can advance both scientifically and economically, stimulating biotechnological growth and sustainable alternatives for public health and the environment.

Keywords: Secondary metabolites, Plant extracts, Phytochemicals, Phenolics, Terpenoids

1.1 Introduction

Bioactive metabolites can be defined as a heterogeneous group of metabolic products synthesized by plants, fungi, bacteria, algae, and animals (Thirumurugan *et al*., 2018). More specifically, plants are regarded as the major producers of these metabolites (Al Aboud, 2024), which are differentially distributed among limited taxonomic groups within the plant kingdom, and various plant compartments are demonstrated to contain bioactive metabolites, including roots, stems, leaves, fruits, and flowers (Jain *et al*., 2019). These metabolites have a wide range of benefits for the producer plants, they use them to interact with other organisms, to defend themselves against environmental stressors and pathogenic microorganisms. Besides, they are also utilized by humans as food additives, for therapeutic, aromatic, culinary, and many other purposes (Yang *et al*., 2018).

The world market for plant bioactive metabolites was worth $4.6 billion in 2022 and is projected to increase further based on increasing demand for natural bioactive molecules (Ghosh *et al*., 2022). Their medicinal value, on the other hand, is gaining importance throughout the world; its international trade is expected to reach USD 5 trillion by 2050. According to research, Asian countries are the major exporters of these plants and their products. This can be utilized to improve the economy of low-income countries (Zahra *et al*., 2019). The provision of regional market statistics and policy data may further complement the assimilation of Kurdistan's phytochemical resources into the global bioeconomy.

It is undeniable that there are plenty of plant species in the Kurdistan region that have various benefits and have been relied upon since ancient times to the present day for different purposes, especially in medicine, flavoring, fragrance, and food industries (Dogara, 2023; Naqishbandi, 2014; Pieroni *et al*., 2017). However, compared to the research and studies that are conducted in Iran and Turkey (Ertas *et al*., 2021; Soltanbeigi & Soltani, 2024), or even across the entire world (Chiocchio *et al*., 2021; Ramírez-Rendon *et al*., 2022), these valuable bioactive metabolites have not been well researched and utilized within the Kurdistan Region. Therefore, this article is trying to fill this gap by focusing on the role of valuable plants and their bioactive compounds in various sectors where Kurdistan is lacking. This is through discussing the existing studies from other countries about their potential applications as insecticides, in agriculture, cosmetics, environmental applications, and the food industry. Additionally, it proposes research directions to integrate these metabolites into sustainable development and commercial applications.

1.2 Plants' bioactive metabolites

Plant's bioactive metabolites are of four major classes: phenolics, terpenes and terpinoids, alkaloids, and sulfur-containing compounds (Sharma *et al*., 2022). They are biosynthesized through several metabolic pathways, including Shikimic-acid, Malonic-acid, Mevalonic-acid, and Methylerythritol-phosphate pathways (Dhaniaputri *et al*., 2022), and they provide the plants with survival strategies since they are generated in response to particular abiotic stresses and pathogenic assaults (Ahmed *et al*., 2017). It worth mentioning that both the biosynthesis and storage of certain compounds are specific to certain organs, tissues, or cells. For example, lipophilic compounds are concentrated in glandular hairs, trichomes, resin ducts, laticifers, thylakoid membranes, or on the cuticle, while hydrophilic compounds are typically stored in vacuoles (Wink, 2010). Typically, flowers, fruits, and seeds serve as reservoir for various bioactive compounds, particularly in annual plants. Besides, the bark of the stems, bulbs, and roots of perennial plants also accumulate a high concentration of metabolites (Wink, 1999).

Several factors contribute to the production and accumulation of metabolites in the plants, including genetic, developmental, and environmental factors. For instance, the accumulation of metabolites is highly dependent on light, temperature, and soil (component, moisture, fertility, and salinity). It was recorded that most plants are susceptible to changes in any one of these factors, even when other factors stay the same (Kandar, 2021; Yang *et al*., 2018). Thus, it can be concluded that seasonal variation and geographical regions could have a high impact on the variations in the biosynthesis of the metabolites.

To identify and choose the plant species for this review, a comprehensive ethnobotanical surveys and literature search were carried out, specifically those plants with significant applications in modern industries and environmental fields worldwide. An initial list of important plants was compiled by examining reports from botanical research institutions and regional biodiversity records. The published studies between 2000–2025 were included in the search, with a focus on more recent works to reflect developments in phytochemical analysis and modern applications.

The following table (Table 1) represents the plant species included in this review, which are available in the Kurdistan region of Iraq, along with their constituent metabolites, as determined by global investigations.

Table 1. Possible secondary metabolite constituents in 21 plant species reported from the Kurdistan region.

Plant species in the region, according to references	**Investigated secondary metabolites with the References**	
Gundelia tournefortii (Kenger) (Abdulrahman, 2023)	• Phenolics (eugenol, methyl eugenol, trans-anethole). •Terpenes (α-terpineol, α-terpinolene, α-farnesene, α-humulene, β-caryophyllene, β-sesquiphellandrene, γ-terpinene, limonene, p-cymene, terpinen-4-ol, zingiberene). • Terpenoids (α-terpinyl acetate, α-copaene, β-bisabolene, linalool acetate). • Phytosterols (campesterol, stigmasterol, *β*-sitosterol). • Phenolic monoterpenoid (carvacrol).	(Halabi *et al*., 2005; Matthäus & Özcan, 2011)
Silybum marianum (Milk thistle) (Hassan & Umer, 2023)	• Phenolics [tannins, silymarin (taxifolin, silychristin, silydianin, silybin A, silybin B, isosilybin A, isosilybin B)]. • Terpene glycosides. • Alkaloids.	(Guemari *et al*., 2020; Javeed *et al*., 2022; Viktorova *et al*., 2019)
Lepidium sativum (Garden cress) (Hassan & Shekha, 2023)	• Phenolics [tannins, flavonols (querectin, kaempferol), flavones (luteolin, apigenin), flavonones (naringin, naringenin)]. • Terpenes (saponins). • Phytosterols. • Alkaloids.	(Chatoui *et al*., 2016; L'hadj *et al*., 2019)
Rheum ribes (Rhubarb) (Amin *et al*., 2023)	•Phenolics (emodin, aloe-emodin, chrysophanol, rhein, chlorogenic acid, gallic acid, tannic acid, kaempferol, rutin, tannins, Quinone, anthraquinones). • Terpenes (curcumin, terpene glycosides). •Alkaloids.	(Abdulla *et al*., 2015; Adham & Naqishbandi, 2015; Noori *et al*., 2022)
Matricaria chamomilla (Chamomile) (Abdulrahman, 2023)	•Terpenes (α-Bisabolol oxide A, β-Farnesene, chamazulene, Guaizulene, α-Bisabolene epoxide, Germacene, Camphor, 3-carene, *β*-myrcene, *α*-phellandrene, *γ*-Terpinene, camphene, *α*-Terpinolen, *α*-Thujenal, myrtenol, sabinol, limonene, caryophyllene, *α*-Muurolene, saponins). • Terpenoids (p-camphorene, p-cymene, *α*-Curcumene, copaene). • Phenolics (2,4,5-tetramethyl1,3-cyclopentadiene, tannins). • Phenolic monoterpenoid (thymol). • Alkaloids. • Phytosterols.	(Ali, 2013; Mohammed & Abdelgadir, 2016; Qasem *et al*., 2022)
Helianthus tuberosus (Jerusalem artichoke) Bakir (2003)	• Phenolics (neochlorogenic acid, chlorogenic acid, caffeic acid, cryptochlorogenic acid, salicylic acid, salvianolic acid, quinic acid, vanillin, cinnamic acid, flavonone (Liquiritigenin), chalcones (butein, kukulkanin B), flavone(nevadensin), astragilin, hymenoxin).	(Kaszás *et al*., 2020; Mariadoss *et al*., 2021)
Beta vulgaris (Beet root) (Abdulrahman, 2023)	• Phenolics (quinone, coumarin, tannins, anthocyanin, gallic acid, catechol, chlorogenic acid, caffeic acid, benzoic acid, syringic acid, p-coumaric acid, pyrogallol, protocatchoic, apigenin, rutin, naringenin, rosmarinic acid, hesperdin, kaempferol, querectin, myricetin, catechin, cinnamic acid, ferulic acid). • Terpenes (saponin, betanin). • Alkaloids (betacyanin).	(El-Beltagi *et al*., 2022; Rehman *et al*., 2022; Zia *et al*., 2021)
Mentha pulegium (Pennyroyal) (Abdulrahman, 2023)	• Phenolics (rosmarinic acid, ellagic acid, chlorogenic acid, eriodictyol, naringenin, α-Humelene, • Terpenes (α-Pinene, β-Pinene, pulegone, piperitenone, Limonene, E-caryophyllene). • Terpenoids (isopulegol). • Phenolic monoterpenoid (thymol).	(Politeo *et al*., 2018; Zekri *et al*., 2013)
Borago officinalis (Star flower) (Ahmed, 2016)	• Phenolics (gallic acid, salicylic acid, pyrogallol, caffeic acid, rutin, myricetin, daidzein, coumarins, hydroxycinnamic acid, tannin). • Terpenes. • Terpenoids (carotenoids (β-Carotene, lutein)). • Sterols.	(Fernandes *et al*., 2019; Gilani *et al*., 2007; Karimi *et al*., 2018; Zribi *et al*., 2019)
Thymus vulgaris *(Garden thyme)* (Ahmed, 2016)	• Phenolic monoterpenoid (carvacrol, thymol). • Terpenes (α-Pinene, β-Pinene, sabinene, α-terpinene, camphor, 1,8-cineole, α-terpineol, carene, δ-Cadinene, terpinen-4-ol, P-cymene, o-cymene, humulene, camphene, α-thujene, D-limonene, γ-terpinene, caryophyllene, β-myrcene, (*E*)-Sesquilavandulol). • Terpenoids (linalool, borneol, α-Cadinol, Geraniol).	(Al-Asmari *et al*., 2017; Borugă *et al*., 2014; Grigore *et al*., 2010; Mancini *et al*., 2015)

Nasturtium officinale (Watercress) (Hassan & Shekha, 2023)	• Phenolics (caffeic acid, gallic acid, salicylic acid, syringic acid, ellagic acid, chlorogenic acid, rutin, •Terpenes (E-phytol, pulegone, squalene, caryophyllene, D-limonene, β-myrcene, β-phellandrene, α-Terpinolene, γ-terpinene). • Sulfur-containing compounds (2-phenylethyl isothiocyanate, heptyl isothiocyanate, 4-phenylbutyl isothiocyanate).	(Boligon *et al*., 2013; Ercan & Dogru, 2022; Quezada-Lázaro *et al*., 2016; Taghavinia *et al*., 2022)
Zingiber officinale (Ginger) (Ahmed, 2016)	• Phenolics (gingerol, lignans (lariciresinol, matairesinol), • Terpenes (β-sesquiphellandrene, cineole, nerolidol B, farnesol 3, Saponins, Zingiberene, curcumene, α-Fernesene, β-farnesene, β-bisabolol, γ-cadinene). • Terpenoids (guaiol, zingiberenol, Carveol, germacrone, Veridiflorol). • Alkaloids.	(Bhargava *et al*., 2012; Osabor *et al*., 2015; Yousfi *et al*., 2021)
Lactuca serriola (Prickly lettuce) (Rasul, 2020)	• Terpenes (hexahydrofarnesyl acetone, phytol). • Terpenoids (α-Terpineol acetate, Germanicol, lupeol).	(Doğan & Servi, 2020; Shukurlu, 2020; Ullah *et al*., 2022)
Anethum graveolens L. (Dill) (Abdullah, 2021)	• Phenolics (tannins). • Terpenes (limonene, saponins, carvone, α-phellandrene, *α*-pinene, myrcene, camphor, p-cymene). • Phenolic monoterpenoid (thymol). • Dill ether and dill apiole.	(Al-bazaz *et al*., 2020; Jana & Shekhawat, 2010; Sharopov *et al*., 2013)
Ocimum basilicum (Basil) (Abdulrahman, 2023)	• Phenolics (rosmarinic acid, Methyl eugenol). • Terpenes (saponins, sabinene, 1,8-cineole, *α-trans-bergamotene,* Bicyclogermacrene*,* transcaryophyllene, *spathulenol, α-cubebene,* B-cubebene, *α-muurolene,* β-elemene, germacrene-D, germacrene-A, limonene, camphor, terpinen-4-ol, *α-humulene)*. • Terpenoids (linalool, geraniol, epi-*α-cadinol,* fenchone, neral, nerol, β-eudesmol, trans-*α-bisabolene,* β-copaene). • Alkaloids. • Phenolic monoterpenoid (carvacrol).	(Fathiazad *et al*., 2012; Oliveira *et al*., 2009; Özcan & Chalchat, 2002; Sanni *et al*., 2008)
Rosa canina (Dog rose) (Al-Mathidy *et al*., 2023)	• Terpenes (β-caryophyllene, α-pinene, β-pinene). • Terpenoids (caryophyllene oxide, linalool, δ-guaiene, β-ionone). • Phenolic (eugenol).	(Hosni *et al*., 2010)
Verbascum thapsus (Mullein) (Amin *et al*., 2020)	• Phenolics (caffeic acid, gallic acid, P-coumaric acid, ellagic acid, Rutin, quercetin, epicatechin, ferulic acid). • Terpenes (squalene). • Phytosterols (stigmasterol).	(Nadeem *et al*., 2021; Soto *et al*., 2022)
Artemisia absinthium (Tarragon) (Ali *et al*., 2021)	• Phenolics (Homorientin, Artemetin, chlorogenic acid, 4-caffeoylquinic acid, 3,4-dicaffeoylquinic acid). • Terpenes (α-Thujene, α-Pinene, α-Terpinene, β-Ocimene, Ocimenone, α-Humulene, γ-Curcumene, trans-Nerolidol, Methyl jasmonate, Chamazulene, α-Muurolene, D-limonene, 1,8-cineole, camphene). •Terpenoids (linalool, Pinocarvone, Bornyl acetate, α-Gurjunene, γ-Gurjunene, Guaiol, γ-Eudesmol, Cubenol).	(Boudjelal *et al*., 2020; Mohammed, 2022)
Malva sylvestris (Mallow) (Abdulrahman, 2023)	• Phenolics (anthocyanosides, 4-hydroxy-benzoic acid, hydroxy-cinnamic acid, ferulic acid, tannins, salicylic acid, oleic acid, apigenin, Scopoletin, coumarins). • Terpenes (phytol, saponin). • Phytosterols (campesterol, stigmasterol). • Alkaloids.	(Al-Rubaye *et al*., 2017; DellaGreca *et al*., 2009; Prod *et al*., 2012)
Spinacia oleracea (Spinach) (Ahmed, 2016)	• Phenolics (tannins). • Terpenes (saponins). •Terpenoids (carotenoids (neoxanthin, violaxanthin, lutein, β-Carotene), ferulic acid, p-coumaric acid, hydroxycinnamate, trans-p-coumarate, o-coumaric acid).	(Bunea *et al*., 2008; Okazaki *et al*., 2008; Tabassum *et al*., 2015)
Coriandrum sativum (Coriander) (Abdulrahman, 2023)	• Phenolics (tannins, coumarins, leucoanthocyanin). •Terpenes (saponins, γ-terpinene, α-Pinene, limonene, α-Thujene, Camphene, sabinene, myrcene, β-pinene, camphor, 1,8-cineole, α-terpinol, germacrene, carvone). • Terpenoids (geranyl acetate, linalool, Cis-dihydrocarvone, neral, nerol). • Alkaloids. •Phytosterols.	(Ahmed *et al*., 2018; Msaada *et al*., 2007; Sasi Kumar *et al*., 2014; Shahwar *et al*., 2012)

1.3 Environmental and Industrial Applications of the Plant's Metabolites

Previous investigations suggest different potential applications of plant metabolites, and this may relate to to their diverse chemical properties and biological activities. However, several challenges are anticipated for their commercial availability and production. Factors such as variability in these natural product's concentration and the absence of regulatory guidelines hinder their environmental and industrial applications and commercialization as well.
Here are some key applications of the metabolites for the above-mentioned plants:

1.3.1 Pharmaceutical applications

Many plants' bioactive metabolites are widely used in pharmaceutical products (Chihomvu *et al*., 2024; Pramanik *et al*., 2024; Sezer *et al*., 2024). Such as in treating cancer (Awasthi & Srivastava, 2024), diabetes (Sezer *et al*., 2024), and managing bacterial and viral infections (Sahoo *et al*., 2024; Mahmoudieh *et al*., 2024). Further details on their pharmaceutical applications are considerably discussed in a separate review article, which is currently in the publication process.

1.3.2 Insecticide applications

Plant-based bioinsecticides are an important group of pesticides that are composed of phytochemicals that prevent harmful insects from damaging edible crops, harming non-target fauna and flora and spreading diseases (Cheraghi *et al*., 2016). They are considered the best alternative to the chemical insecticides, as they are eco-friendly, less toxic to untargeted organisms, and less prone to pest resistance. They possess a diverse mode of actions, allowing them to act as insect repellents, or anti-feedants (Khursheed *et al*., 2022).
Several plants in the Kurdistan region have this property and can be used as insecticides, as shown in the Table 2:

Table 2. Insecticidal activities of the reported plant species.

Plant Species	Bioactive constituents	Insecticidal activities	References
G. tournefortii	Extracts	Inhibit the growth of vinegar fly *Drosophila melanogaster Meigen*	(Ghabeish, 2015)
L. sativum	Extracts	Effective against mosquito larvae	(Al-Keridis *et al*., 2021; Ayoub *et al*., 2023)
M. chamomilla	Essential oils	Effective insecticides against red, black, and hybrid imported fire ants	(Al-Ghanim *et al*., 2023; Mihyaoui *et al*., 2022), (Shah *et al*., 2023)
M. pulegium	Essential oil monoterpene and sesquiterpene hydrocarbons, and alkaloids	Effective in pest control	(Aimad *et al*., 2021; M. Domingues & Santos, 2019)
T. vulgaris	Essential oil	Has acute toxicity against the larvae of *Spodoptera littoralis* and *Culex quinquefasciatus.*	(Pavela & Sedlák, 2018).
		Reduces adult survivability, deters female egg laying, and strongly inhibits adult emergence of *Acanthoscelides obtectus*	(Lazarević *et al*., 2020)
Z. officinale	Gingerols and shogaols	Effective against: *Spodoptera* spp	(Keosaeng *et al*., 2023)
	Extracts	*Aedes aegypti* larvae	(Boekoesoe & Ahmad, 2022)
		Red flour beetle	(Kadhim & Younis, 2023)
A. graveolens	Essential oils	Effective against: *Rhyzopertha dominica*	(Jayakumar *et al*., 2021)
		Sitophilus zeamais Motschulsky	(Chaubey, 2021)
		Cochlochila bullita	Bendicion *et al*., 2020
O. basilicum	Extracts	Effective against: Tobacco cutworm *Spodoptera litura* Feb. (Lepidoptera; Noctuidae)	(Jafir *et al*., 2021)
		Acanthoscelides obtectus	(Rodríguez-González *et al*., 2019)
		South American tomato moth	(Prasannakumar *et al*., 2023)
		Sitophilus oryzae	(Bincy *et al*., 2023)
R. canina	Extracts	Effective against *Rhopalosiphum padi*	(Benslama *et al*., 2021)
C. sativum	Extracts	As an insecticide	(Amoabeng *et al*., 2019; Kassahun, 2020)

1.3.3 Agricultural applications

The sustainable management of crop production in modern agriculture involves dealing with many different challenges. Balancing crop productivity with environmental sustainability is one of the main challenges for agriculture worldwide (Kostina-Bednarz *et al*., 2023). As described by (Kisiriko *et al*., 2021), the phenolic compounds and extracts from some medicinal and aromatic plants can be used as biostimulants and bioprotectants in agriculture, such as those from *Z. officinale*.

Furthermore, plant metabolites can also be used as eco-friendly herbicides to control weeds, which can significantly reduce the use of synthetic herbicides. This can be achieved by spraying crop fields with the plant extracts containing allelopathic compounds (Kostina-Bednarz *et al*., 2023). To illustrate, research has shown *M. chamomilla* as a viable source for bioherbicide production to control flixweed (*Descurainia sophia L.*) (Madadi *et al*., 2022), specifically to inhibit germination and growth of Durum wheat (*Triticum turgidum* L. subsp. durum (Desf.) Husn.) (Elbouzidi *et al*., 2021).

Several allelochemical compounds in the extracts of specific plant species can be successfully used as effective bioherbicides against weeds, like phenols and flavonoid compounds in *C. sativum* seed powder (El-Rokiek *et al*., 2020), it's essential oil (El-Rokiek *et al*., 2021; Sumalan *et al*., 2019), the extract of *N. officinale* (Khan *et al*., 2021; Wang *et al*., 2024), caryone and limonene in the essential oil of *A. graveolens* (Dorina, 2020; Mirmostafaee *et al*., 2020; Saric-Krsmanovic *et al*., 2023), the essential oils of *O. basilicum* (Anupama *et al*., 2023; Kamel *et al*., 2022), the extracts of *L. serriola* (Heivachi *et al*., 2023), and *M. sylvestris* (Tatari *et al*., 2020).

Finally, the flavonoids and phenolic acids from extracts of *C. sativum* (Sriti *et al*., 2022) along with monoterpenes from its essential oil (Barros *et al*., 2022) were found to have strong repellent activities against different insects.

1.3.4 Skin Care applications

Cosmetic products have various plant-based active ingredients that serve diverse functions; they can provide nutrients for hair, increase skin elasticity, enhance skin collagen, have anti-aging properties, have antioxidants to resist UV radiation, reduce hyperpigmentation, and many others benefit skin health (Bashir *et al*., 2021). The plant metabolites that are used for skin protection due to their antioxidant and UV-protection activity are illustrated in Table 3. One of the main environmental roles of plants

Table 3. UV-protectant bioactive metabolites from the reported plant species.

Plant Species	Bioactive constituents	References
S. marianum	Silymarin	(Drouet *et al*., 2018, 2019; Fehér *et al*., 2016)
T. vulgaris	Rosmarinic acid and thymol	(Cornaghi *et al*., 2016; Sun *et al*., 2017)
O. basilicum	Essential oil	(Malapermal *et al*., 2015)
M. chamomile	Essential oil	(Mustafakulovna & Kurbonalievna, 2022)
N. officinale	Indole 3-acetonitrile-4-methoxy-2-S-β-D-glucopyranoside in its oil	(Chaudhary *et al*., 2018)
R. canina	Ascorbic acid, tannins, and phenolics	(Taneva *et al*., 2016)
S. olerancea	Carotenoids	(Michalak, 2022)
B. officinalis	Phenolics, flavonoids, and fatty acid	(Karimi *et al*., 2018)

Plant metabolites are also utilized in hair and scalp care products. According to research, phenolic compounds, alkaloids, and other beneficial compounds extracted from the seeds of *L. sativum* are believed to reduce hair loss and prevent hair from turning grey (Syeda Kaniz *et al*., 2022). Moreover, the seed mucilage was also used in natural hair conditioners to make hair smoother, decrease hair strand friction, and make brushing easier (Patil, 2019). Other research shows that the essential oil of *M. chamomile* can lighten hair and be used in scalp care products (Mustafakulovna & Kurbonalievna, 2022), *R. canina* fruit extract can be used in aerosol hair sprays (Johnson *et al*., 2022), and the essential oil of *A. dracunculus* can be used as an active ingredient in nail, hair, and bath items (Coltun, 2021).

Skin care products may also contain plant metabolites. Some of them may be used as antiaging agents to reduce wrinkles and improve skin elasticity, especially in moisturizing products, such as silymarin in *S. marianum* extract (Drouet *et al*., 2019). Several plant extracts and essential oils enhance skin elasticity and result in firmer skin, as shown in Table 4.

Table 4. The extracts and essential oils of reported plant species that improve skin texture.

Plant Species	Bioactive constituents	References
M. chamomile	Essential oil	(Mustafakulovna & Kurbonalievna, 2022)
T. vulgaris	Extracts	(Caverzan et al., 2021)
N. officinale	Extracts	(Klimek-Szczykutowicz *et al*., 2018)
O. basilicum	Essential oil	(Yaldiz *et al*., 2023)
V. sinatuam	Polyphenol	(Donn *et al*., 2023)
C. sativum	Essential oil	(Salem *et al*., 2022)
A. graveolens	Carvone, d-limonene, and α-phellandrene in seed extract	(Sohm *et al*., 2011)

In addition, the essential oil of *M. chamomile,* which is a rich source of bisabolol, can soothe irritation, deodorize, fight bacteria, and provide after-shave treatments, making it widely popular for use in lip care, infant skin care, and hair removal products (Mustafakulovna & Kurbonalievna, 2022). Another research mentioned that azulene in the essential oil of chamomile flowers is valued in skincare for its gentle, soothing qualities and its ability to moisturize and help remove residue, making it a useful ingredient in products designed for sensitive skin or post-hair removal care (Elsharkawy *et al*., 2014). Jerusalem artichoke is another useful plant whose extract is used in skin care products. According to studies, it can be used in producing two-phase makeup removers (Niziol-Lukaszewska *et al*., 2020), related to flavonoid and phenolic compounds in its extracts, which play a role in promoting skin health and supporting repair processes (Nizioł-ŁUkaszewska *et al*., 2018). Using color is one of the features in cosmetic products; to exemplify, *B. vulgaris* was used as a natural dying agent, which can be added to henna for hair and skin, and also was used in producing herbal lipstick due to its high carotenoid and betacyanin (betanin) red color (Chaudhari *et al*., 2019; Insan & Vera, 2021; Obat & Bosire, 2022; Rosaini *et al*., 2021). Moreover, several compounds, like flavonoids,

saponins, tannins, alkaloids, quinones, triterpenoids, and steroids in beetroot extracts, are beneficial for formulating various skincare products, such as creams, blushes, and powders (Sari *et al*., 2021).
Other benefits of plant metabolites in cosmetics include skin infection treatment and acting as an anti-acne agent (Table 5).

Table 5. Plant species that are used to treat acne and skin infections**.**

Plant Species	Bioactive constituents	References
T. vulgaris	Extract	(Silva *et al*., 2021)
N. officinale	Extract	(Klimek-Szczykutowicz *et al*., 2018)
Z. officinale	Extract	(Tritanti & Pranita, 2019)
R. canina	Extract	(Johnson *et al*., 2022)
L. serriola	Azulene in its oil	(Elsharkawy *et al*., 2014)

As a whitening agent: *Z. officinale* and its active ingredient, zerumbone (ZER), can decrease the expression of melanogenesis-related genes, which has the potential to be beneficial in skin-whitening products (Oh *et al*., 2018). Umbelliprenin in the seed extracts of *A. graveolens* was also used as an anti-hyperpigmentation drug and as an ingredient for skin-lightening cosmetics (Taddeo *et al*., 2019).
Some of the plants contain highly aromatic bioactive compounds that can be used in the manufacture of perfumes and fragrances. *L. serriola* oil extract's pleasant aroma relates to sesqui sabinene hydrate, limonene oxide, thunbergol, and globulol, which makes it suitable for use in the perfumery industry (Elsharkawy *et al*., 2014). Besides, *A. graveolens* seeds extract (Sohm *et al*., 2011), essential oil of *O. basilicum* (Avetisyan *et al*., 2017), *R. canina* extracts (Javanmard *et al*., 2018; Johnson *et al*., 2022), and the essential oil extracted from *A. dracunculus* (Coltun, 2021) have been used in this industry.

1.3.5 Environmental applications

The negative impacts of conventional agriculture production and the expanding human population on the environment can be managed by using plants with diverse metabolites (Clemensen *et al*., 2020).
One of the main environmental roles of plants is phytoremediation, a process that decontaminates soil and water by absorbing pollutants (Khan *et al*., 2019; Singer *et al*., 2003). These metabolites can scavenge reactive oxygen, precipitate, and chelate metal ions from the surroundings (Anjitha *et al*., 2021). This might be regarded as one of the main ways to remediate heavy metals and degrade pollutants from soil, and as a new option for wastewater management (Amiri *et al*., 2020; Moustafa *et al*., 2020).
Several plant species have been shown to accumulate different kinds of heavy metals from contaminated soils and waters, which may suggest their strong potential as bioremediation agents. Compared to known hyperaccumulators such as *Brassica juncea*, which has been reported to accumulate up to 16.750 mg/kg of Zn in leaves and 7.170 mg/kg of Cu in stems (Sut-Lohmann *et al*., 2023), Kurdistan plant species exhibit comparable or even higher uptake capacities. For example, *G. tournefortii* has demonstrated adsorption capacities of 38.7597 mg/g for copper and 144.928 mg/g for lead (Golshan Shandi *et al*., 2019; Rahimpour *et al*., 2017). Similarly, *S. marianum* has been shown to accumulate lead, cadmium, and zinc in quantities far exceeding the maximum permissible levels (Razanov *et al*., 2020). Several other species display promising phytoremediation potential. *L. sativum* accumulates mercury (Hg) in its aerial tissues to over 12% of total Hg from polluted soil with 10 mg/kg of Hg (Smolinska & Leszczynska, 2017). *H. tuberosus was* recorded as a mercury hyperaccumulator (Lv *et al*., 2018; Montalbán *et al*., 2017), while *L. serriola* shows significant copper uptake, reaching 46 mg/kg (Abou-Shanab *et al*., 2017). Other notable phytoremediators include *C. sativum,* which phytoremediates lead and arsenic from tailing soil, with recorded concentration of 44.52 ± 0.65 ppm arsenic in the leaf, and 350.88 ± 0.33 ppm lead in the root (Garrett *et al*., 2019; Gaur *et al*., 2017), *O. basilicum* has been found to phytoextract cadmium from soils with 116 mg/kg accumulated in the root (Adiloğlu, 2021; Alamo-Nole & Estrella-Martinez, 2022; Dinu *et al*., 2020). Additionally, *N. officinale* can inhibit urease activity in the soil and accumulate cadmium (2.23 mg/L) (Ali *et al*., 2025; Jarosz *et al*., 2023; Zhang *et al*., 2019). Further research highlights *V. thapsus* as a copper accumulator to a maximum level (492.8 mg/kg in shoots and 447.3 mg/kg in roots (Kavousi *et al*., 2021; Khan *et al*., 2024), *A. absinthium* can be used as the most practical way for remediation of copper-contaminated soils (Ghazaryan *et al*., 2022), while *M. parviflora* was suggested as the best for phytoextracting heavy metals and lead cleanup with a concentration capacity of 5.76 mg/kg (Shaaban *et al*., 2025). Lastly, *S. oleracea* exhibits good potential for Cd phytoextraction with a concentration ranging from 1.59 to 50 mg/kg (Chaturvedi *et al*., 2019; Ugulu *et al*., 2022).

On the other hand, some plants were shown to bioremediate drugs, such as *O. basilicum* to remediate amoxicillin (Bhatt & Gauba, 2021), and *S. oleracea* to remediate paracetamol (Badar *et al*., 2022).

Equally important, several plant species can degrade and decrease certain pollutants in the environment; to illustrate, *N. officinale* is used to decrease greenhouse gases by producing urease inhibitors (Hube *et al*., 2017; Jarosz *et al*., 2023). *O. basilicum* and *R. canina* are used to absorb and remove methylene blue dye from water (Alikhani *et al*., 2022; Gupta & Verma, 2022; Karaghool *et al*., 2022). *M. parviflora* to remove Disperse Blue 183 and Maxillon Blue GRL dyes from water (Alkadir *et al*., 2022).

Moreover, plants can also be used as bio-indicators for ecotoxicological diagnostic and environmental quality investigations through the use of their metabolites as biomarkers (Ferrat *et al*., 2003; Marciulioniene *et al*., 2019). To illustrate: *L. sativum* was used recently by researchers to measure soil and water phytotoxicity (Mañas & De las Heras, 2018). Further, *H. tuberosus* to detect phenol pollutant concentration in soil (Odaci *et al*., 2004).

Furthermore, plant extracts and metabolites have been used in the green synthesis of eco-friendly nanoparticles with fewer environmental hazards (Kumar *et al*., 2020), which is useful in a broad range of fields such as healthcare, cosmetics, the chemical industry, food, and feed (Song *et al*., 2020). It could also help in environmental bioremediation, solving the problems of water purification and quality (Turakhia *et al*., 2018).

It is worth mentioning that some plants are toxic to some pests, including insects, fungi, and bacteria, and their effect have been associated with their secondary metabolites (Cespedes *et al*., 2015). Using these plants as pesticides can be advantageous over chemical ones in controlling pests, and having no harmful impacts on the environment and human beings (Yadav *et al*., 2022). These beneficial plants include the flowers of *M. chamomilla*, which can be used as eco-friendly bio-fungicides (EL-Hefny *et al*., 2019), *T. vulgaris* (Lazarević *et al*., 2020; Livingstone & Matheen, 2023; Zahed *et al*., 2021), and *M. pulegium* (Attia *et al*., 2022; M. Domingues & Santos, 2019).

On the other hand, saponin is another useful eco-friendly material due to its natural origin and biodegradability. To date, many plant-based saponins have been investigated for their surfactant properties, and their activities in many fields such as antimicrobial, antidiabetic, anticancer, adjuvant potentials, and others are reported. These surfactants offer great potential for the replacement of toxic synthetic surfactants (Rai *et al*., 2021). For example, *G. tournefortii* was explored for its use in optimizing chemically enhanced oil recovery for chemical EOR applications in 2021 (Bahraminejad *et al*., 2021).

Another application is the use of plant extracts as an ideal, cheap, eco-friendly candidate to replace traditional toxic metal corrosion inhibitors (Verma *et al*., 2018). Green corrosion-inhibiting plant extracts contain water-soluble metabolites like organic acids, quinone, phenolic compounds, flavonoids, alkaloids, catechins, terpenoids, and co-enzymes, making them easily applicable in many industrial fields (Verma *et al*., 2018). In this respect, *R. ribes* was used to protect steel and copper from corrosion (Kaya *et al*., 2023a, 2023b). *B. vulgaris* peel extract has shown anti-corrosive behavior against SS 410 surface in 15% hydrochloric acid (Bhardwaj *et al*., 2022). Spinach extract has both biocidal and corrosion inhibition properties (Parthipan *et al*., 2021). *S. oleracea* was used as a green corrosion inhibitor for carbon steel (Hameed *et al*., 2022).

Natural fiber-reinforced composites are another environmentally safe, long-lasting, and recyclable material derived from plants (Dalmis, 2023). It is worth mentioning that metabolites like lignin, cellulose, and hemicellulose, as well as their compound types like ester, ketone, and alcohol, are the main components of natural fibers (Fan *et al*., 2012). *H. tuberosus* stalk particles are used to produce cement-bonded particleboards for construction applications (Wang *et al*., 2016), and its fiber is used for polymer-based green composites (Dalmis, 2023). The use of a naturally-derived membrane from *M. Verbascum* is considered a green technology to reduce the use of non-green chemicals (Saleh *et al*., 2021). Finally, a bio-based dye by *B. vulgaris* can be used as an eco-friendly dye to stain wool and cotton as a substitute for synthetic pigments, which pose a hazardous impact on the environment and humans (Benli, 2022; Patel & Patel, 2022).

1.3.6 Food industries

With the rise of healthy food diets and people's demand for no addition of synthetic materials, new methods for food production and preservation are vital. Natural plant constituents are one of the best ways to help the food industry and production (Petropoulos, 2023). In this part, this review will discuss the potential role of plant metabolites in this field, especially as preserving, flavoring, texturizing, and coloring agents (Kallscheuer *et al*., 2019).

Plant metabolites with antioxidative properties find applications as preservatives or anti-browning agents, thus helping to preserve food and extend its shelf life, meeting consumer demands (Kallscheuer *et al*., 2019). Several plant-derived secondary metabolites are useful as food preservatives due to their significant antioxidant capacities, as follows:

The seed gum of *L. sativum* exhibited a high antioxidant capacity (~85%) when used for beef and cheese preservation (Esmaeili *et al*., 2021; Rehim *et al*., 2023). The antioxidant activity of *M. chamomilla* essential oil was recorded with an EC_{50} value of 2.07 mg/ml (Stanojevic *et al*., 2016). Similarly, the antioxidant activity of *M. pulegium* essential oil ranged from 7.5 to 44.7 µg/mL (Salehi *et al*., 2018). While the essential oil of *T. vulgaris* recorded an antioxidant capacity of 85.2 ± 0.2% Galovičová *et al*., 2021). Additionally, the extract of *Z. officinale* proved to have a great radical scavenging activity of 54.5% (Murphy *et al*., 2020). The essential oil of *A. graveolens* L. exhibited antioxidant capacity with an IC_{50} value of 9.02 mg/mL (Hadi *et al*., 2024), whereas the fruit extract of *R. canina* fruit recorded an IC_{50} value of 89.16 ± 2.76 µg/mL (Soltan *et al*., 2023). Moreover, the extracts of *S. oleracea* showed significant antioxidant capacity with values of 34.89 µg/mL and 35.60 µg/mL (Salehi *et al*., 2019), Finally, the free radical scavenging assay for the essential oil of *C. sativum* was noted to be 39.38 mg/L (Kačániová *et al*., 2020).

Another benefit of some of these plants in the food industry is their use as flavoring agents. Examples are: natural compounds in *Z. officinale* can be useful in foods as herbs, spices, flavorings, and seasonings (Mara Teles *et al*., 2020), essential oil of *T. vulgaris* (Almanea *et al*., 2019; Pavela & Sedlák, 2018), *Z. officinale* (Laelago *et al*., 2023; Shahrajabian *et al*., 2019), the essential oil of *A. graveolens* L.(Kaur *et al*., 2018), oil and oleoresin of sweet basil *O. basilicum* (Egata, 2021), and the essential oil of *C. sativum* (Al-Khayri *et al*., 2023).

Food fortification is one way that food gets processed in the food industry, which is the act of improving the nutritional value of a food by increasing or adding micronutrients (Darnton-Hill & Nalubola, 2002). According to investigations, phytonutrients from many plants are used to biofortify food, feed, and medicines (Sreenivasulu & Fernie, 2022). Examples of plants whose metabolites are utilized in this area are included in Table 6.

Table 6. Bioactive plant extracts from the reported plant species that are used in the food fortification industry.

Plant Species	Bioactive constituents	References
H. tuberosus	Extracts	(Apostol *et al*., 2019; Catană *et al*., 2018)
S. marianum	Seed extracts	(Lukic *et al*., 2022) (Krystyjan *et al*., 2022) (Dabija *et al*., 2018)
L. sativum	Seed extracts	(Lahiri & Rani, 2020)
M. chamomilla	Extracts	(Caleja *et al*., 2016; Caleja *et al*., 2016)
A. graveolens	Extracts	(Paven *et al*., 2018)
R. canina	Extracts	(Kubczak *et al*., 2020)
A. absinthium	Extracts	(Bordean *et al*., 2021; Boulares *et al*., 2023)
M. pulegium	Extracts	(Habibvand *et al*., 2023)
Z. officinale	Ginger oil and oleoresin	(Imamović *et al*., 2021)

Besides, the biologically active plant compounds of some of the plants have the potential to be used in the packaging of food as alternatives to petroleum-based polymers that yield enormous amounts of plastic waste. According to research, the compounds that can be used in food packaging as an edible coating include phenols and flavonoids (Rehim *et al*., 2023). The plants used for this purpose include *L. sativum* (Rehim *et al*., 2023) and *T. vulgaris* (Razavi *et al*., 2021; Silva *et al*., 2021). Finally, *B. vulgaris* is one of the common plants that can be used as a food colorant due to betalains in its constituents (Corleto *et al*., 2018; Domínguez *et al*., 2020; Kumar & Brooks, 2018).

1.4 Safety and risk assessments

While Kurdistan plants' metabolites hold high environmental and industrial potential applications, their commercial exploitation is hampered by challenges in standardization, industrial feasibility, and regulatory approval.

Currently, there are no comprehensive studies assessing the GRAS (Generally Recognized As Safe) status of metabolites derived specifically from Kurdistan's plant species (FDA, 200). Therefore, performing safety evaluations, concentrating on establishing evaluation standards, quality control, and collaborating with regulatory agencies for the approval process are considered important steps for future initiatives. Moreover, factors such as yield optimization, extraction efficiency, and cost play a crucial role in determining whether these bioactive compounds can be produced at an economically viable scale (Sagar, *et al*., 2024; Heinrich *et al*., 2022; Tariq *et al*., 2021). Further, clinical and toxicological research, exploring modern techniques like CO_2 supercritical extraction (Chen *et al*., 2024) may offer promising advancements in metabolite recovery for large-scale production. Similarly, metabolic engineering and tissue culture methods could enhance secondary metabolite yield (Fazili *et al*., 2022; Hesami *et al*., 2021; Mipeshwaree Devi *et al*., 2023; Ozyigit *et al*., 2023). By resolving these regulatory issues, Kurdistan's plant metabolites could gain broader acceptance in various industrial markets around the world.

Conclusions

Using natural bioactive compounds from plants is gaining importance worldwide as an alternative to unsafe chemicals, in which researchers have deliberately investigated their side effects.
The Kurdistan region is home to a rich diversity of plant species, many of which possess valuable metabolites and significant environmental and industrial applications. As noted from the above-mentioned works, the plant's metabolites have been utilized globally in various industries, including pharmaceuticals, insecticides, agriculture, cosmetics, the environment, and food. Local utilization in daily life and research investigations into these valuable resources are still limited. This review strongly suggests the necessity of investing these metabolites in further research and contribution to future biotechnological advancements. Besides, implementing this natural wealth in further applications may represent a promising avenue to stimulate the growth of the economy and development. Moreover, the valuable species of high marketing value should be conserved, and their cultivation should be promoted for future use.

Author contributions

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Conflicts of Interest

The authors declare no conflicts of interest.

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