

# Plant Nutrition for Human Health

Subjects: [Agriculture, Dairy & Animal Science](#)

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Is there any relationship between plant nutrition and human health? The overall response to this question is very positive, and a strong relationship between the nutrition of plants and humans has been reported. The nutritional status of edible plants consumed by humans can have a negative or positive impact on human health.

nutrients

degraded soil

plant secondary metabolites

elevated CO<sub>2</sub>

## 1. Introduction

There is increased concern about the concept of medicinal plants for human health and their importance for general well-being, rather than solely for consumption as human foods <sup>[1]</sup>. These plant foods represent the main source for most mineral macro- and micro-nutrients, which are essential elements for human nutrition, as well as a range of bioactive ingredients, which can support preventing many chronic diseases such as Alzheimer's, cataracts, cancer, cardiovascular disease, diabetes, and age-related functional decline <sup>[1][2]</sup>. Therefore, vegetable and fruit plants are important parts of the human diet, which can contain proteins, carbohydrates, amino acids, fatty acids, lipids, and vitamins (i.e., A, B complex, C, E, and K). Edible plants could be applied in the field of phytomedicine because of their nutritional value, which mainly is due to the high contents of the previously mentioned compounds, in addition to many bioactive ingredients for overcoming several human diseases <sup>[3][4][5][6][7]</sup>. Several current reports have been published that investigate the role of agro-techniques (different agricultural technologies) in producing plant bioactives by using plant tissue culture tools <sup>[8][9]</sup> or agro-wastes such as banana peels <sup>[10]</sup>, olive mill pomace <sup>[11]</sup>, and coffee leaves <sup>[12]</sup>.

## 2. Plant Nutrients Uptake and Their Physiological Functions

Cultivated plants need nutrients for their growth and development, including essential (e.g., N, P, K, Ca, Mg, Mn, Fe, B, Zn) and beneficial nutrients (e.g., Se, Si, Na). When the cultivated plants can uptake all required nutrients, this will be reflected in the productivity, which will be higher. Plants contribute significantly to the global food chain by providing elements such as carbohydrates, proteins, edible oils, dietary fibers, vitamins, and minerals in forms such as vegetables, fruits and grains <sup>[13][14]</sup>. They also supply us with medication, clothing, construction materials, biofuels, pulp, and other products. As a result, improved plant growth and health would directly benefit nations' economies and development <sup>[15]</sup>. Plant nutrition is concerned with the relationship between soil nutrients and plant development <sup>[16]</sup>. Plants require at least 14 mineral elements in addition to O<sub>2</sub>, CO<sub>2</sub>, and H<sub>2</sub>O for optimal nutrition. Plant development and agricultural production are reduced when any of these minerals are deficient. Six mineral elements are required in large quantities, these being N, P, K, Ca, Mg, and S, whereas Cl, B, Fe, Mn, Cu, Zn, Ni, and Mo are required in small quantities <sup>[17]</sup>. The uptake of nutrients for plant growth under different environmental conditions may be influenced by the soil conditions, especially degraded soils such as salt-affected soils. The main problem that faces cultivated plants under salt-affected-soil conditions is salinity and/or alkalinity stress, which may lead to deficiency of some nutrients and/or some physiological disorder in the leaves of these cultivated plants (**Figure 1A,B**).



(A)



(B)

**Figure 1.** (A) Plant growth under different environmental conditions may cause a problem in uptake of some nutrients from soils, especially degraded soils such as salt-affected soils. The main problem that faces cultivated plants under salt-affected-soil conditions is salinity and/or alkalinity stress, which may lead to deficiency of some nutrients. These photos represent some nutrient deficiency and/or some physiological disorder in the leaves of some cultivated horticultural crops. All photos of guava, apricots, pears, and peaches were taken from the experimental farm at Kafrelsheikh University by El-Ramady. (B) More photos of the obstacles facing cultivated plants under degraded conditions in particular salt-affected soils. The main problem that faces cultivated plants under salt-affected-soil conditions is salinity and/or alkalinity stress, which may lead to deficiency of some nutrients. These photos represent some nutrient deficiency and/or some physiological disorder in the leaves of some cultivated horticultural crops. All photos of citrus, pears, and guava plants were taken from the experimental farm at Kafrelsheikh University by El-Ramady.

Mineral nutrients play an essential function in plant metabolism. A lack of any mineral nutrient inhibits plant growth, which has a direct relationship with the plant's production potential (**Table 1**). Mineral nutrients are involved in the creation of vital organic molecules such as amino acids and proteins, and nutritional imbalance can affect a variety of biological processes [18]. Nutrient deficiency and toxicity adversely affect crop health, resulting in the emergence of strange visual symptoms and

decreased crop yields <sup>[16]</sup>. To increase yields in locations with limited phytoavailability, important mineral elements are applied to the soil as fertilizers. Furthermore, fertilizers with critical minerals for human nutrition are periodically applied to crops in order to boost their concentrations in edible parts for the benefit of human health <sup>[17]</sup>.

**Table 1.** A list of nutrient biological functions in plants and suggested deficiency symptoms.

| Nutrient Element | Nutrient Symbol | Uptake Form                                     | Nutrient Biological Functions in Plants [Ref.]  | Deficiency Symptoms of Nutrients [Ref.]   |
|------------------|-----------------|---|---|---|
| Nitrogen         | N               | $\text{NH}_4^+$ and $\text{NO}_3^-$             | Constituent of amides, amino acids, proteins, nucleic acids, nucleotides, coenzymes, chlorophyll, etc. <sup>[19]</sup>  | Inhibits plant growth; yellowing or chlorosis of leaves due to a collapse in chloroplasts <sup>[20]</sup>                                       |
| Phosphorus       | P               | $\text{H}_2\text{PO}_4^-$ ; $\text{HPO}_4^{2-}$ | Constituent of nucleic acids and lipid membranes, ATP, etc. <sup>[21]</sup>   | Dark greenish-purple leaves, with necrotic spots and malformed <sup>[21]</sup>  |
| Potassium        | K               | $\text{K}^+$                                    | Controls more than 60 enzymes, mainly of photosynthesis and respiration <sup>[22]</sup>   | Chlorosis of older leaves; shorter internodes in stems; inhibiting protein synthesis <sup>[21]</sup>  |
| Calcium          | Ca              | $\text{Ca}^{2+}$                                | Ca-pectate is main constituent of cell wall; controls elongation and division of cells; activates many enzymes <sup>[19]</sup>                                | Small and younger leaves; deformed and chlorotic, bitter pit (apple); black heart (celery) <sup>[22]</sup>                                      |
| Magnesium        | Mg              | $\text{Mg}^{2+}$                                | Component of chlorophyll and polyribosomes; enzyme cofactor <sup>[23]</sup>   | Chlorosis of intervein and streaked or patchy effects on leaves <sup>[22]</sup>   |
| Sulfur           | S               | $\text{SO}_4^{2-}$                              | Component of amino acids (i.e., cysteine, cystine, and methionine), CoA and vitamins (biotin; thiamine), and glucosides in onions <sup>[16]</sup>             | Interveneal chlorosis. S-deficiency chlorosis in all leaves at the same time; yellowish-green <sup>[21]</sup>                                   |
| Boron            | B               | $\text{H}_2\text{BO}_3^-$                       | Involved in many processes: proteins synthesis, respiration, sugars transport metabolism of RNA, plant hormones, and carbohydrate <sup>[24]</sup>             | Mainly appears on younger leaves; malformed and bluish-green; retaining flowers, forming of pollen <sup>[19]</sup>                              |
| Copper           | Cu              | $\text{Cu}^{2+}$                                | Essential respiration and photosynthesis of mitochondria; component of major enzymes Cu-Zn-SOD <sup>[24]</sup>  | Necrosis, spots at tips of younger leaves, white tips, die back, and reclamation disease <sup>[21]</sup>  |
| Chlorine         | Cl              | $\text{Cl}^-$                                   | Essential for osmoregulation and photosynthesis; increases resistance to plant diseases (rice; barely; corn) <sup>[25]</sup>                                  | Leaf chlorosis, curling of leaves, plant wilting, and restricted branching in root system <sup>[24]</sup>                                       |
| Iron             | Fe              | $\text{Fe}^{2+}$                                | Essential for respiration; assimilation of N, mitochondria, photosynthesis; hormones biosynthesis; cytochromes; Fe-containing proteins (haem) <sup>[24]</sup> | Interveneal chlorosis from younger leaves; leaf margins and veins remain green; stunted growth in palms leads to meristem death <sup>[26]</sup> |
| Nickel           | Ni              | $\text{Ni}^{+2}$                                | Essential for prokaryotic enzymes such as hydrogenases, dehydrogenases; component in urease enzyme <sup>[27]</sup>  | Leaf-tip necrosis; nitrate in leaves accumulation; Ni deficiency in pecan called mouse-ear leaves <sup>[27]</sup>                               |
| Manganese        | Mn              | $\text{Mn}^{2+}$                                | Exists in several plant cell enzymes; involves many enzymes (i.e., lyases, hydrolases); proteins Mn-SOD <sup>[28]</sup>                                       | Interveneal chlorosis in dicots; smallest leaf veins remain green; speckled yellow in sugar beet <sup>[19]</sup>                                |
| Molybdenum       | Mo              | $\text{MoO}_4^-$                                | Essential for N-assimilation, phytohormone  | In young plants: dwarfed plants, mottling, grey tinting, cupping and flaccid leaves <sup>[16]</sup>   |

| Nutrient Element | Nutrient Symbol | Uptake Form      | Nutrient Biological Functions in Deficiency Symptoms of Nutrients Plants [Ref.]                       | [Ref.]  |
|------------------|-----------------|------------------|---|---|
|                  |                 |                  | biosynthesis S-metabolism; controls N-assimilation enzymes [24]                                       |   |
| Zinc             | Zn              | Zn <sup>2+</sup> | Component of synthesis protein enzymes; essential catalytic for more than 300 enzymes, Zn-Cu-SOD [19] | Interveneal chlorosis; internodes short, younger shoots; smaller leaves; malformed, rosetted [22] |

O) [18][29], in the soil. These H<sup>+</sup> displace cations linked to negatively charged soil particles, making them accessible for root absorption. Stomata open in the leaves to take in CO<sub>2</sub> and exhale O<sub>2</sub>. In photosynthesis, CO<sub>2</sub> molecules serve as a C supply. The root, particularly the root hair, is a vital organ for nutrient intake. The root's morphology and architecture can influence nutrient absorption [18]. The nutrients required by plants are supplemented by fertilizers with the belief that they are mainly absorbed by plants. Micronutrient deficiency is shown by irregular development of plant tissues; nevertheless, this may not mean the soil is insufficient for micronutrients; rather, the root may be unable to absorb and translocate the nutrients due to limited root pore size. To fulfill the demands for food of the rising population, it is consequently critical to investigate techniques for boosting crop quality and key nutrients [30].

Plant growth and development are strongly influenced by the combination and concentration of available mineral nutrients in the soil. Because of their relative immobility, plants frequently encounter considerable challenges in receiving an appropriate supply of essential nutrients to fulfill the demands of basic cellular functions. A lack of any of the required elements may result in reduced plant production and/or fertility. Nutrient deficiencies can induce stunted growth, plant tissue death, or leaves yellowing due to a decrease in the production of chlorophyll, a pigment required for photosynthesis. A lack of nutrients can have a substantial influence on agriculture, resulting in lower crop yield or plant quality. The nutrient deficit can also limit overall biodiversity, because plants are the producers that support the majority of food webs [31]. By 2100, the world population is expected to reach 11.0 billion. As a result, existing food production must be increased by 60–70% to fulfill the calorie demands of the rising population. Global future food demand can only be met by improving resource usage efficiency without reducing agricultural yields by advancing current science and technology. Chemical fertilizers have increased agricultural productivity in developing countries by 50–55%. However, the usage efficiency of supplied nutrients via fertilizers remains relatively low (N: 30–40%, P: 15–20%, K: 50–55%, and micronutrients: 2–5%). This results in excessive soil nutrients mining, resulting in a net negative soil nutrient balance of about 10 million tons and hence deteriorating soil health [32].

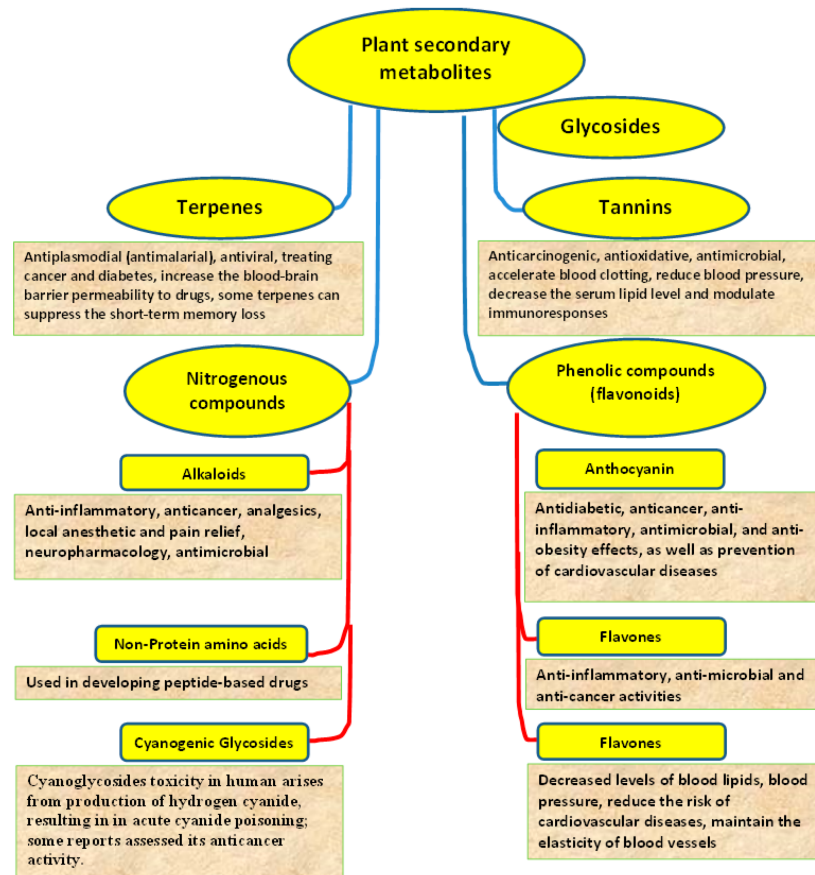
### 3. Medicinal Plants and Their Bioactive Compounds

Medicinal plants are defined as plants that have a wide variety of bioactive compounds exhibiting several biological activities and beneficial properties, including antioxidant, antiviral, antimicrobial, anticancer, anti-inflammatory, anti-aging, antihypertensive, and neuroprotective attributes [33]. Medicinal plants are of great potential all over the world, due to their healthy consumption and/or their application as extract supplementation for traditional medication. A remarkable number of studies can be found on the therapeutic attributes of medicinal plants combined with a growing concern for their use as natural products (e.g. [34][35][36][37]). Medicinal plants represent 25–50% of the current production of drugs that are used in the sector of healthcare from various sources [36]. It is expected that the medicinal plant field will continue supporting new medicine derived from natural products during the coming decades [35]. The mode of action of these medicinal plants mainly depends on the extracted/used parts, including flowers, leaves, fruits, roots, seeds, and stems, which are considered rich sources of bioactive compounds [38].

It is well known that medicinal plants can be consumed as fresh foods or applied as extracts to foods or pharmaceutical products. For selecting medicinal plants, there are different strategies that can be used. Concerning plant functional traits and their potential for human health, there are several general themes such as antimicrobial plants [39][40], plant secondary metabolites [41], nutraceuticals for human health [42], plant leaf protein concentrates [43], biofortified plants for human health [44], plant-based diets for human diseases [7][45], and herbal bioactive-based products for different applications such as cosmetics [46][47]. Plant-based diets have important benefits for human health, which prevent or decrease many human diseases such as cardiovascular, dermatological, endocrinological, gastrointestinal, ophthalmological, genitourinary, otolaryngological, musculoskeletal, neurological, and respiratory diseases [39].

All plant species can form primary metabolites in cells, but secondary metabolites vary by plant species and can be produced through metabolic pathways derived from the primary metabolic pathways. Both primary (e.g., chlorophyll, carbohydrates, fats, proteins, lipids, and nucleic acids) and secondary metabolites are active compounds in plants that have a variety of functions. Plant secondary metabolites could be defined as organic compounds that are produced by plants but are not directly involved in plant biological processes, including growth, development, and reproduction [48]. These metabolites have numerous functions in plants, including plant growth and development processes, innate immunity, defense response

signaling, and response to environmental stresses [49] as well as root microbiomes [50] (Figure 2). Secondary metabolites can also be used as food additives, pharmaceuticals, and cosmetics ingredients [51]. Enormous plants, mainly medicinal plants, that can produce bioactive secondary metabolites include Chinese medicinal herbs, as reported by El-Ramady et al. [52] and in Table 2 and Table 3. The production of bioactive plant secondary metabolites is common using in vitro technologies [53][54].



**Figure 2.** The major groups of plant secondary metabolites could in general be classified into many large molecular families such as alkaloids, flavonoids, phenolics, terpenes, and steroids as well as by their therapeutic effects on human health.

On the other hand, nutraceuticals have great potential for human health. They can help and support the absorption of vitamins and minerals, preventing their deficiency. They can also inhibit harmful biochemical reactions, detoxify cells, facilitate the growth of beneficial microbiota, and excrete out wastes [55]. Nutraceuticals have some medical properties such as anti-aging, antioxidant, and anti-cancerous attributes, which can enhance different biochemical processes and structures [55]. These attributes also may augment phagocytosis, induce immunomodulatory effects, enhance immune response, prevent hypersensitivity, and reduce auto-immune response [56]. Nutraceuticals can help prevent and cure many diseases related to cancer, diabetes, neurodegeneration, and hypertension [42].

The world suffers from chronic undernourishment, especially in Africa and Asia. Therefore, different natural sources for human nutrition are very important, including animal sources and traditional or underutilized plants. Consumption of plants is important, whether they are consumed as a fresh source for human nutrition or as extracts added to foods or to drugs due to their high contents of bioactive compounds. Therefore, several traditional, wild, or underutilized plants, including many vegetables and legumes, could be consumed by humans to improve human health (Table 2). These plants contain certain bioactive compounds or phytochemicals (e.g., alkaloids, lectins, glucosinolates, organic acids, polyphenols, terpenes, and volatiles), which have important roles in preventing several chronic human diseases such as diabetes, cancer, and diseases of the heart, through many biological activities such as anticancer, antioxidant, antihypertensive, antimicrobial, anti-inflammatory, and hepatoprotective attributes [57].

**Table 2.** List of some underexploited or underutilized plants, their used part, their common use, and their bioactive compounds as medicinal plants. All scientific names according to Plants of the World Online (<https://powo.science.kew.org/>, accessed on 25 June 2022).



| Common Name(s)                  | Scientific Name   | Plant Family   | Commonly Used Plant Part(s)     | Common Uses                                    | Refs. |
|---------------------------------|---|----------------|---------------------------------|--|-------|
| Adzuki bean                     | <i>Vigna angularis</i> (Willd.) Ohwi and H. Ohashi        | Fabaceae       | Seeds                           | Seeds for cooking with rice                    | [58]  |
| Andean lupin, pearl lupin       | <i>Lupinus mutabilis</i> Sweet                            | Fabaceae       | Seeds                           | Seeds for culinary use                         | [59]  |
| African yam bean                | <i>Sphenostylis stenocarpa</i> Hochst ex. A. Rich. Harms  | Fabaceae       | Seeds, tubers                   | Seeds for culinary use                         | [60]  |
| Bambara nut or groundnut        | <i>Vigna stenocarpa</i> L. Verdc                          | Fabaceae       | Seeds                           | Seeds for foods and beverages                  | [61]  |
| Deer-eye beans, donkey-eye bean | <i>Mucuna</i> spp.  | Fabaceae       | Seeds                           | Seeds for culinary use                         | [62]  |
| Jack beans, sword bean          | <i>Canavalia</i> spp.                                     | Fabaceae       | Pods and seeds                  | Pods as vegetable; seeds for culinary use      | [63]  |
| Ground bean, Hausa groundnut    | <i>Macrotyloma geocarpum</i> (Harms.) Maréchal and Baudet | Fabaceae       | Seeds like peanuts              | Seeds for culinary use                         | [64]  |
| Hyacinth bean, lablab bean      | <i>Lablab purpureus</i> L.                                | Fabaceae       | Leaves, seeds                   | Seeds used culinarily                          | [65]  |
| Horse gram                      | <i>Macrotyloma uniflorum</i> (Lam.) Verdc.                | Fabaceae       | Seeds                           | Seeds for culinary use                         | [66]  |
| Peavines, vetchlings            | <i>Lathyrus</i> spp.                                      | Fabaceae       | Pods, seeds                     | Seeds for culinary use                         | [67]  |
| Moth bean                       | <i>Vigna aconitifolia</i> (Jacq.) Marechal                | Fabaceae       | Pods, seeds                     | Seeds for culinary use                         | [68]  |
| Stinky bean                     | <i>Parkia speciosa</i> Hassk.                             | Fabaceae       | Pods, seeds                     | Pods and seeds for culinary use                | [69]  |
| Rattlepods                      | <i>Crotalaria</i> spp.                                    | Fabaceae       | Leaves, flowers, pods, seeds    | Leafy vegetable; seeds for culinary use        | [70]  |
| Rice bean                       | <i>Vigna umbellata</i> (Thunb.) Ohwi and H. Ohashi        | Fabaceae       | Seeds                           | Seeds for culinary use                         | [71]  |
| White lead tree, subabul        | <i>Leucaena leucocephala</i> (Lam.) de Wit                | Fabaceae       | Pods                            | Young pods used as vegetable                   | [72]  |
| Winged bean                     | <i>Psophocarpus tetragonolobus</i> (L.) D.C.              | Fabaceae       | Leaves, seeds, bean pods, roots | Entire winged been plant is edible             | [57]  |
| Amaranth                        | <i>Amaranthus</i> spp.                                    | Amaranthaceae  | Leaves, seeds                   | Leafy vegetable, oil, pigments                 | [73]  |
| Black nightshade                | <i>Solanum nigrum</i> L.                                  | Solanaceae     | Leaves, fruits (berries)        | Leaves and berries as food prepared by cooking | [74]  |
| Common purslane                 | <i>Portulaca oleracea</i> L.                              | Portulacaceae  | Leaves, stem                    | Leafy vegetable                                | [75]  |
| Curcuma                         | <i>Curcuma</i> spp.                                       | Zingiberaceae  | Rhizomes, roots, leaves         | Roots edible, rhizomes culinary                | [76]  |
| Bitter melon, spiny gourd       | <i>Momordica</i> spp.                                     | Cucurbitaceae  | Fruits                          | Fruits as vegetable                            | [57]  |
| Indian poke                     | <i>Phytolacca acinose</i> Roxb.                           | Phytolaccaceae | Leaves                          | Leafy vegetable                                | [57]  |
| Mallow leaves                   | <i>Corchorus</i> spp.                                     | Malvaceae      | Leaves                          | Leafy vegetable                                | [57]  |

| Common Name(s)             | Scientific Name                           | Plant Family   | Commonly Used Plant Part(s) | Common Uses                  | Refs. |
|----------------------------|---|----------------|-----------------------------|------------------------------|-------|
| Parsnip                    | <i>Pastinaca sativa</i> L.                | Apiaceae       | Roots                       | Root vegetable like carrot   | [57]  |
| Prickly pear               | <i>Opuntia</i> spp.                       | Cactaceae      | Leaves or cladodes          | Leaves cooked as a vegetable | [62]  |
| Squash, pumpkin            | <i>Cucurbita</i> spp.                     | Cucurbitaceae  | Leaves, fruits, seeds       | Fruits for culinary          | [77]  |
| Sea kale                   | <i>Crambe</i> spp.                        | Brassicaceae   | Leaves                      | Leafy vegetable              | [57]  |
| Tassel hyacinth            | <i>Leopoldia comosa</i> (L.) Parl.        | Asparagaceae   | Bulbs                       | Bulbs as vegetable           | [78]  |
| Tomatillo                  | <i>Physalis philadelphica</i> Lam.        | Solanaceae     | Fruits                      | Green fruits as vegetable    | [57]  |
| Yellow cresses             | <i>Rorippa indica</i> (L.) Hiern          | Brassicaceae   | Tender shoots, leaves       | Leafy vegetable              | [57]  |
| Water spinach              | <i>Ipomoea aquatica</i> Forssk.           | Convolvulaceae | Leaves                      | Leafy vegetable              | [79]  |
| Water leaf, Ceylon spinach | <i>Talinum triangulare</i> (Jacq.) Willd. | Talinaceae     | Leaves                      | Leafy vegetable              | [80]  |

On the other hand, several bioactives derived from plants have been used in therapeutic applications. Before these applications, certain strategies are required to identify these bioactive compounds in plant extracts through a guide for identification of bioactive compounds. These strategies depend on the plant extract, its bioactivity pattern, and the facility of isolation. In general, the main strategies that can be used in the identification of bioactive compounds from plant extracts may include bioactivity-guided fractionation, synergy-directed fractionation, a metabolic profiling approach, a metabolism-directed approach, and direct phytochemical isolation [81]. However, more research on this topic needs to be undertaken before the association between plant bioactives and therapeutic activities is more clearly understood. Recently, a great concern for plant bioactives and therapeutic agents has been reported in the literature (e.g. [51][81][82]), as reported in **Table 3**.

**Table 3.** List of some important medicinal plants and their bioactive compounds and their therapeutic applications or medicinal effects. All scientific names according to Plants of the World Online (<https://powo.science.kew.org/>, accessed on 25 June 2022).

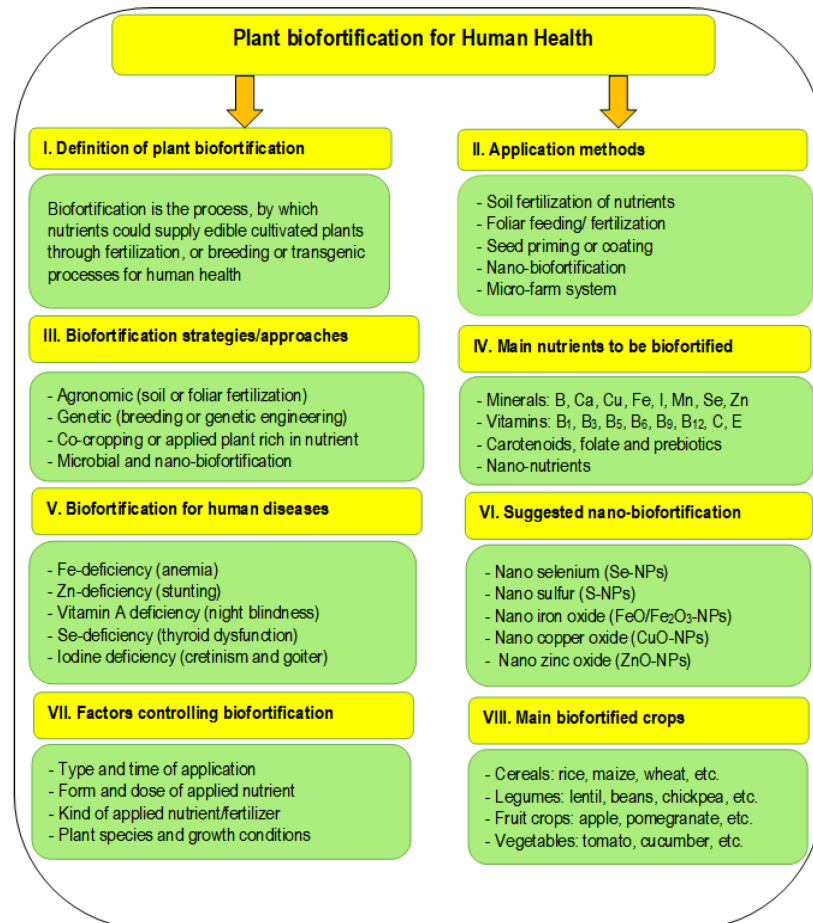
| Plant Species  | Therapeutic Agent              | Target Disease                                     | Ref. |
|--|--------------------------------|--|------|
| <i>Artemisia annua</i> L.                                    | Artemisinin                    | Malignant treatment                                | [83] |
| <i>Artemisia obtusiloba</i> Ledeb.                           | Arglabin                       | Cancer chemotherapy                                | [81] |
| <i>Amorpha fruticosa</i> L.                                  | Monoterpene and sesquiterpene  | Antibacterial, insecticidal, and cytotoxic effects | [51] |
| <i>Calophyllum lanigerum</i> Miq.                            | Calanolide A                   | Type-1 HIV   | [51] |
| <i>Capsicum annum</i> L.                                     | Capsaicin                      | Postherpetic neuralgia treatment                   | [81] |
| <i>Cannabis sativa</i> L.                                    | Dronabinol; Cannabidiol        | Chronic neuropathic pain                           | [81] |
| <i>Caragana sinica</i> (Buc'hoz) Rehder                      | Collagen and aggrecan          | Preventing degradation of cartilages               | [84] |
| <i>Carthamus tinctorius</i> L.                               | Serotonin/N-feruloyl serotonin | Preventing degradation of cartilages               | [85] |
| <i>Cephalotaxus harringtonia</i> (Knight ex J.Forbes) K.Koch | Homo-harringtonine             | Oncology treatment                                 | [81] |
| <i>Colchicum</i> spp.  | Colchicine                     | Gout disease                                       | [81] |
| <i>Conium maculatum</i> L.                                   | Coniine                        | Poisonous, neurotoxin                              | [86] |
| <i>Cinchona succirubra</i> Pav. ex Klotzsch                  | Quinine                        | Antimalarial                                       | [87] |
| <i>Dalbergia sissoo</i> Roxb. ex DC.                         | Flavonoids (Tectorigenin)      | Anti-degradation of cartilage proteins             | [88] |
| <i>Euphorbia peplus</i> L.                                   | Ingenol mebutate               | Actinic keratosis treatment                        | [81] |
| <i>Galanthus woronowii</i> Losinsk.                          | Galantamine                    | Alzheimer's disease                                | [89] |

| Plant Species                                     | Therapeutic Agent          | Target Disease                               | Ref.  |
|---|----------------------------|--|-------|
| <i>Galega officinalis</i> L.                      | Metformin                  | Anti-diabetic                                | [51]  |
| <i>Larrea tridentata</i> (DC.) Coville            | Masoprocol                 | Cancer chemotherapy                          | [81]  |
| <i>Nigella sativa</i> L.                          | Thymoquinone               | Osteoarthritis treatment                     | [82]  |
| <i>Oroxylum indicum</i> (L.) Kurz                 | Oroxilin A                 | Anti-degrading markers of cartilages         | [90]  |
| <i>Papaver somniferum</i> L.                      | Morphine                   | Acute pulmonary disease and breath shortness | [91]  |
| <i>Papaver somniferum</i> L.                      | Codeine                    | Analgesic and anti-diarrheal properties      | [92]  |
| <i>Papaver bracteatum</i> Lindl.                  | Thebaine (paramorphine)    | Analgesic                                    | [93]  |
| <i>Phyla nodiflora</i> (L.) Greene                | Nepetin                    | Osteoarthritis treatment                     | [94]  |
| <i>Rhus succedanea</i> L.                         | Rhoifolin                  | Preventing degradation of cartilages         | [95]  |
| <i>Pueraria lobata</i> (Willd.) Ohwi              | Puerarin                   | Against cartilage degradation                | [96]  |
| <i>Sarcotheca griffithii</i> (Planch.) Hallier f. | Crude extract              | Cough  | [97]  |
| <i>Solanum</i> spp.                               | Nicotine                   | Anti-inflammatory and stimulant              | [98]  |
| <i>Solanum tuberosum</i> L.                       | Solanine                   | Anticarcinogenic                             | [99]  |
| <i>Solanum lycopersicum</i> L.                    | Tomatine                   | Anticancer and immune effects                | [100] |
| <i>Talinum triangulare</i> (Jacq.) Willd.         | Acrylamide and phaeophytin | Cuts, wound, scabies, and peptic ulcer       | [101] |
| <i>Taxus brevifolia</i> Nutt.                     | Paclitaxel                 | Antimitotic agent for various cancers        | [81]  |

#### 4. Plant Nutrition Management for Human Health

Mineral malnutrition is unfortunately a common problem in both developing and industrialized countries, with estimates suggesting that up to two-thirds of the world's population may be at risk of deficiency in one or more critical mineral elements [102][103]. Nutrient deficiency is considered one of humanity's most severe concerns, from which millions of people suffer. According to Brevik et al. [104], at least 25 mineral elements are likely to be required for human health, and plants are the main providers of the majority of these nutrients. Iron (Fe), Zn, I, Se, Ca, Mg, and Cu are the most deficient mineral elements in the human diet [105]. For a variety of reasons, edible plants may not contain enough mineral elements for human nutrition. These reasons may include the genetics of plant species with low content of certain mineral elements, differences between crops in their mineral phytoavailability (such as for Cu, Fe, and Zn in alkaline or calcareous soils), and plant anatomy, including restricted phloem mobility of elements in edible portions such as seeds, fruits, and tubers at low concentrations [17]. Therefore, there is an urgent need to produce edible plants with sufficient and proper nutrients for human nutrition, which could be achieved using many strategies, especially biofortification approaches [106]. The application of nutrients to cultivated plants is called biofortification, which can be achieved by agronomic and genetic biofortification and nanobiofortification (Figure 3).





**Figure 3.** Biofortification process, including the definition, applied methods, different strategies, different nutrients that can be biofortified, factors controlling this process, and the main crops, which can be biofortified.

The biofortification process is effective in enriching many crops, mainly staples, with nutrients such as Fe, Cu, Mn, Ca, Zn in addition to folate and vitamins [\[107\]\[108\]\[109\]\[110\]](#). The enrichment of food with essential or required nutrients is called fortification. The main reason for biofortification is fighting hidden hunger, which results from consumed foods not having enough nutrients (essential vitamins and micronutrients such as Fe, Cu and Zn), especially in sub-Saharan Africa and South Asia [\[111\]](#). Thus, a long history of food fortification all over the world is known, including margarine, butter, and sugar using vitamin A, salt (fluoride and iodine), and milk using vitamins [\[111\]](#). The historical background of biofortification may include conceptualization (1950–1990), realization using research (1990–2000), and producing of biofortified crops (2001–2020) [\[111\]](#).

Plant nutrition management is one of the most important global challenges that faces human life, and it must be managed with a holistic approach through responsible plant nutrition [\[112\]](#). The future of plant nutrition and its challenges can be highlighted using this approach as a new paradigm that depends mainly on the food system and circular economy to achieve multiple environmental, socioeconomic, and health objectives. This new paradigm for managing plant nutrients could be presented through the following questions, as suggested by Dobermann et al. [\[112\]](#):

- How can the world increase crop productivity to double its current amount, especially under the global nutrient imbalance?
- How can the world guarantee this production to double or triple, particularly in developing countries such as African nations under unbalanced inputs of human nutrition?
- What is the role of precision or smart farming in accelerating the adoption by farmers of more solutions for precise nutrient management?
- What are the sustainable solutions for decreasing the losses of nutrients, such that their wastes along the whole agri-food chain are halved?
- To what extent can the nutrient cycles in the farming of crops and livestock be made closed?
- What are the key measures to improve and sustain soil health?
- What is the main role of mineral nutrition of different crops and its changes in a changing climate?
- To what extent can applied fertilizers reduce greenhouse gas emissions?

- What is the main role of cropping systems in producing high crop quality and more nutritious foods?
- To what extent can we monitor nutrients for implementation of 4R nutrient stewardship?

Therefore, the sound management of plant nutrition can be achieved when this management overcomes the main problems that face plant nutrition through the following objectives: (1) improving nutrient efficiency, crop productivity, and then farmer income, (2) increasing the recovery of nutrients and their recycling from wastes, (3) improving and sustaining soil health and its quality, (4) enhancing human health with tailored nutritious crops, and (5) minimizing greenhouse gas emissions, nutrient pollution, and biodiversity loss <sup>[112]</sup>. In the following sub-sections, it is shown that some challenges facing plant nutrition can be managed in some selected case studies, including climate change conditions, pollution, and problematic soil, with focus on plant bioactive compounds.

#### 4.1. Plant Nutrition under Climate Change

Climate change affects all of human life, especially the agricultural sector, in addition to the fields of environment, ecosystems, socio-economics, and socio-politics <sup>[113]</sup>. Climate change has threatened the sufficient supply of food and its production due to irreversible weather fluctuations <sup>[114]</sup>. Due to several shifts in optimum temperature ranges of many plant species, climate change has influenced the survival of many species, thereby accelerating the loss rate in their biodiversity and changing the ecosystem structure <sup>[114]</sup>. Plants are undergoing considerable environmental change as a result of human activities, such as climate change caused by increases in atmospheric CO<sub>2</sub> and other greenhouse gasses, which is raising average and severe high temperatures and changing precipitation patterns. Climate change, as a crucial component of global ecosystems, has had a profound impact on human, plant, and animal cycles and processes. For optimal growth and development, the plants need some mineral nutrients, which are significant components of a variety of macromolecules (i.e., nucleic acids, phospholipids, amino acids, and co-enzymes). These molecules play a role in plant cellular metabolism, and it is reflected positively in physiological properties of the plant (i.e., chlorophyll synthesis, redox reactions, plasma membrane integrity, and cell osmotic potential), as reported by Soares et al. <sup>[115]</sup>. Furthermore, these climatic changes are significantly related to water-use efficiency, drought sensitivity, and high geographic variability in soil nutrients, which provide a complex environment that influences soil microbial activity and nutrient availability. The impact of climate change on plant nutrition, including nutrients and their availability to cultivated plants, has reported by Elbasiouny et al. <sup>[116]</sup>

To understand how plants respond and adapt to these climatic changes, several studies have looked into the problem from various angles, such as the effects of N and increased CO<sub>2</sub> or N and water stress on various elements of plant structure and function, as well as the impacts of CO<sub>2</sub> on the quality of plant as food and nutrient translocation within plants. Three homologous pairs of species common in semi-arid environments in California have been studied using serpentine soils (usually high in Mg and low in Ca and N) and non-serpentine soil <sup>[117]</sup>. The authors showed that non-serpentine species were more tolerant for a wider range of nutrients and water, owing to their rapid growth and greater capacity to adapt than serpentine species. Furthermore, they expected that high water availability and nutrients would benefit all species more than low water availability and nutrients. In addition, they measured plant growth responses in the context of functional traits (e.g., relative growth rate, root mass ratio, and photosynthetic nitrogen-use efficiency) in a greenhouse study, and one of their key findings was that functional traits based on nutrient use and allocation explained more response variability than other traits. Furthermore, they discovered that, contrary to expectations, species responded best to a mix of low water and high nutrients, regardless of their origin. Under elevated CO<sub>2</sub> concentrations from 400 to 800 ppm, the accumulation of nutrients, especially K and Mg, was significantly increased, whereas phosphorus was decreased in leaves, stems, and roots of *Asparagus racemosus* <sup>[118]</sup>.

Ayi et al. <sup>[119]</sup> showed that *alternanthera philoxeroides*, or alligator-weed, is a common and often invasive plant that is invasive near waterways and tolerant of flooding. They measured plant growth and root anatomical change in response to varying oxygen or nutrient concentrations in independent hydroponic trials. Results showed root efficiency declined as plants allocated more biomass to roots in response to decreased nutrients, primarily by developing longer, thinner roots, resulting in increased root surface area. Plant responses to lower oxygen concentrations were unexpected; for example, root efficiency was highest at the lowest oxygen concentration. Under low N conditions, Xu et al. <sup>[120]</sup> found that one rice cultivar, Takanari, maintained its high yielding advantage over other cultivars at increased CO<sub>2</sub>. According to the research, this cultivar could be a helpful genetic resource for enhancing N-use efficiency under increased CO<sub>2</sub>. In addition, Li et al. <sup>[121]</sup> investigated the impacts of increased CO<sub>2</sub> on the nutritious content of soybean seeds, while Dong et al. <sup>[122]</sup> described the findings of a meta-analysis to quantify the effects of increased CO<sub>2</sub> on the nutrient content of other vegetables. Several reports have been published on the role of global climate change in the decline of crop productivity and soil fertility due to the exposure of these soils to many frequent features of climate change such as higher temperatures, droughts, floods, desertification, and salinization resulting from extreme weather events (e.g., <sup>[123][124][125]</sup>).

Potential climate change and plant bioactive compounds were discussed in a survey, which included some published studies (e.g. [126][127]). The production of plant secondary metabolites (as bioactives) may also depend on climate change, which represents both high temperatures and elevated CO<sub>2</sub> [128]. The expected impact of climate change on plant bioactive compounds is generally negative and may return to the crucial effect of climate on plant productivity as abiotic stress. A high-heat-mediated increase in many plant bioactives (e.g., alkaloids, flavones, and terpenes) has been found in various plant species such as *Catharanthus roseus*, *Quercus rubra*, and *Brassica oleracea* [128]. Recently, a study on the effect of elevated concentrations of CO<sub>2</sub> on the secondary metabolites or bioactive compounds content of different plant species was reported by Lupitu et al. [129]. They found that the contents of total flavonoids and polyphenols were decreased under elevated CO<sub>2</sub> (up to 1200 ppm or  $\mu\text{mol mol}^{-1}$ ), whereas the emission of monoterpenes increased for the studied *Brassicaceae* plants. This response to elevated CO<sub>2</sub> depends on the studied plant species, as presented in Table 5.

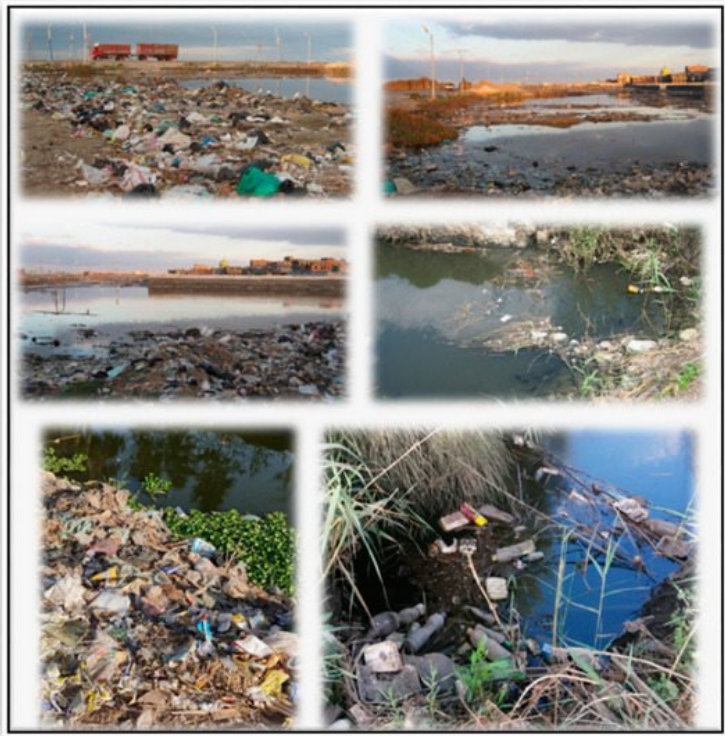
**Table 5.** Some published studies about effects of changed climatic elements on plant bioactive compounds. All scientific names according to Plants of the World Online (<https://powo.science.kew.org/>, accessed on 25 June 2022).

| Studied Plant   | Climate Change Factor  | Plant Bioactive Compound and Its Response   | Ref.  |
|---|--|---|-------|
| Purple rice ( <i>Oryza sativa</i> L.)                               | Low light intensity  | Shading increased total anthocyanin and total phenol compounds  | [130] |
| <i>Catharanthus roseus</i> (L.) G. Don                              | Ultraviolet-B (UV-B) irradiation for 5 min   | Increased alkaloids (catharanthine, vindoline)  | [131] |
| <i>Fagopyrum esculentum</i> Moench                                  | Three treatments of UV-B   | Increased phenolics (quercetin, catechi, rutin)   | [132] |
| <i>Gnaphalium luteoalbum</i> L.                                     | Two different levels of irradiance UV-B  | Increased phenolics (flavonoids: calycopterin and 3'-methoxycalycopterin)   | [133] |
| <i>Camptotheca acuminata</i> Decne.                                 | Heat stress (from 34 to 46 °C at 2 °C intervals)   | Increased alkaloids (10-hydroxycamptothecin)  | [134] |
| <i>Daucus carota</i> L.   | Heat stress (incubated at 44 °C)   | Decreased terpenoids ( $\alpha$ -terpinolene)   | [135] |
| <i>Quercus rubra</i> L.   | Heat stress (at 20/14 and 32/24 °C)  | Increased terpenoids (isoprene, 2-methyl-1,3-butadiene)   | [136] |
| <i>Daucus carota</i> L.   | Heat stress (18 and 21 °C)   | Decreased terpinolene ( $\alpha$ -terpinolene with increasing growth temperature)   | [137] |
| Dropwort ( <i>Oenanthe stolonifera</i> L.)                          | Elevated CO <sub>2</sub> at 600 and 1000 $\mu\text{mol mol}^{-1}$                        | Total phenolics/cyanidin/antioxidant capacity of plantlets increased by high eCO <sub>2</sub>   | [138] |
| <i>Asparagus racemosus</i> Willd.                                   | Elevated CO <sub>2</sub> 400, 600, and 800 $\mu\text{mol mol}^{-1}$                      | Elevated CO <sub>2</sub> increased the content of total sugars and proteins in leaves and roots   | [118] |
| Summer savory ( <i>Satureja hortensis</i> L.)                       | Elevated CO <sub>2</sub> (620 $\mu\text{mol mol}^{-1}$ )                                 | Nutrients (K, Ca, P, Mg) and polyphenols were enhanced by eCO <sub>2</sub> under drought stress   | [139] |
| Caraway ( <i>Carum carvi</i> L.)                                    | Elevated CO <sub>2</sub> at 400 and 620 $\mu\text{mol mol}^{-1}$                         | Higher CO <sub>2</sub> enhanced content of phenolic compounds and flavonoids  | [140] |
| Barley ( <i>Hordeum vulgare</i> L.) and maize ( <i>Zea mays</i> L.) | eCO <sub>2</sub> level (620 $\mu\text{mol mol}^{-1}$ )                                   | Barley accumulated anthocyanins, but total phenolics and flavonoids accumulated in maize under As <sub>2</sub> O <sub>3</sub> -NP stress and elevated CO <sub>2</sub> | [141] |
| Two species of lemon-grass  | Elevated CO <sub>2</sub> (620 $\mu\text{mol mol}^{-1}$ )                                 | eCO <sub>2</sub> increased level of primary and secondary metabolites such as amino acids and phenolics   | [142] |
| <i>Paris polyphylla</i> var. <i>yunnanensis</i>                     | Elevated CO <sub>2</sub> (800 $\mu\text{mol mol}^{-1}$ )                                 | A high-CO <sub>2</sub> environment increased the diosgenin content and thus total saponin   | [143] |
| <i>Glehnia littoralis</i> Fr. Schmidt ex Miquel                     | Elevated CO <sub>2</sub> (500, 1500 $\mu\text{mol mol}^{-1}$ ) under 3 light intensities | Higher light intensities (300) induced higher content of total saponin and chlorogenic acid, whereas no significant effect from eCO <sub>2</sub>                      | [144] |

| Studied Plant                                  | Climate Change Factor  | Plant Bioactive Compound and Its Response  | Ref.  |
|--|--|--|-------|
| Tea ( <i>Camellia sinensis</i> L.)             | Elevated CO <sub>2</sub> at 406 and 770 μmol mol <sup>-1</sup> | Elevated CO <sub>2</sub> significantly increased the polyphenols and theanine in tea seedlings     | [145] |
| <i>Gynostemma pentaphyllum</i> (Thunb.) Makino | Elevated CO <sub>2</sub> at 360 and 720 μmol mol <sup>-1</sup> | Elevated CO <sub>2</sub> led to decreased accumulation of total phenolics and flavonoids in leaves | [146] |

4.2. Plant Nutrition under Pollution

Pollution is considered a global problem facing all countries in the world due to its potential impacts on human health and entire ecosystems (Figure 4). This pollution creates an urgent need for green lungs in different urban parks and general gardens, especially in cities (Figure 5).



**Figure 4.** Pollution is considered one of the most important problems facing the entire world even in developed or developing countries, especially pollution resulting from human activities such as domestic wastes (sewage sludges), plastic wastes, sludges disposed of into irrigation canals, and other wastes. All photos of different irrigation canals and urban areas from Egypt by El-Ramady.



**Figure 5.** Fighting pollution in cities or urban areas may require establishing public gardens and parks as presented in these photos, which represent new lungs for the city to generate the necessary  $O_2$  and remove the  $CO_2$  in the atmosphere. The first and second photos from the top row are from Vienna (Austria), the 3rd and 4th photos are from Debrecen (Hungary), the 5th and 6th photos are from Cairo (Al-Azhar-park, Egypt), and the 7th and 8th photos are from München, left, and Halle Saale, right (Germany). All photos by El-Ramady.

Pollution does not only affect cultivated plants or human health but also affects the health of the complete ecosystem depending on the kind of pollution, such as microplastic, sewage sludge, electronic wastes, mining wastes, and human wastes [147]. The problems that face plant nutrition under pollution stress may depend on the type of pollutants, their concentration, the medium of pollution (soil, air, water, etc.), and plant species. Cultivated plants in polluted soils are thought to be the primary source of highly hazardous element accumulators, which are classified as accumulator plants, hyper-accumulator plants, and excluder plants based on the content of hazardous materials they absorb. Toxic components could potentially accumulate and spread from soil to plant, water to plant, and air to plant [148]. Therefore, hazardous elements in the polluted environment have a negative impact on plant growth, even at low or high metal concentrations. Toxic elements can harm the photosynthetic process, slow the growth of plants, and cause oxidative stress, and at high concentrations, they can stymie plant growth by interfering with the photosynthetic process and altering the coordination of vital elements and their functional mechanisms [149]. Human activities are the main source for environmental pollution in the context of urbanization and industrialization, which may include pollution from polycyclic aromatic hydrocarbons, heavy metals, polychlorinated biphenyls, pesticides, dioxins, ultrafine particles, etc. [150]. Several studies have shown that almost all biological plant processes impacted by pollution and its criteria, such as photosynthetic rate, plant leaf respiration, protein synthesis, plant metabolic processes, and crop growth, were significantly impacted and destroyed in polluted soils [96][151][152].

According to previous studies, several cultivated plants are negatively influenced by pollutants such as toxic elements, especially the plants' bioactive compounds (Table 6). It is reported that Cd toxicity ( $120 \text{ mg kg}^{-1}$ ) reduced the growth parameters, physiological modifications, antioxidant enzymes, and yield of lettuce plants [153]. More recent studies were published to focus on many human diseases (e.g., the impairment of gonadal development and male fertility) resulting from a polluted human diet. At the global level, there is an urgent need to establish an ideal dietary profile, including different diet patterns, to improve health status and reduce the mortality from different human diseases [150].

The cultivation of plants in soil polluted with heavy metals (HMs) is considered to result in abiotic stress, which forces plants to generate oxygen-free radical species (ROS), causing damage in plants in the following forms: (1) disruption of cell homeostasis, (2) DNA-strand breakage, (3) protein defragmentation, (4) damage in pigments, and (5) plant cell death [154]. Therefore, the accumulation of HMs in plants restricts their growth, impairs their structure, and damages their biochemical and physiological activities as well as bioactive compounds, depending on the kind of HMs, their toxicity, and whether it is chronic.



This may lead to permanent damage to many human organs, such as the lungs, brain, kidney, and liver [154]. The growing of plants, particularly medicinal plants, in soil polluted with HMs may impact the biosynthesis of secondary metabolites/bioactives, causing significant changes in the quality and quantity of these bioactive compounds [155][156].

**Table 6.** Some published studies on abiotic stress, including pollution and its impacts on plant bioactive compounds. All scientific names according to Plants of the World Online (<https://powo.science.kew.org/>, accessed on 25 June 2022).

| Studied Plant  | Abiotic Stress Details  | Plant Bioactive Compound and Its Response   | Ref.  |
|--|---|---|-------|
| <i>Robinia pseudoacacia</i> L.                             | Applied Cd at 0.45 and 4.5 mg Cd kg <sup>-1</sup>                                     | Elevated CO <sub>2</sub> (up to 750 ppm) may promote synthesis of total flavonoids under Cd stress  | [157] |
| Potato ( <i>Solanum tuberosum</i> L.)                      | Drought stress by discontinued irrigation for 6 weeks after 88 days planting          | No significant effect of drought on phenolic compounds, anthocyanins, or antioxidant activity   | [158] |
| Feverfew ( <i>Tanacetum parthenium</i> (L.) Sch. Bip.)     | Drought stress (irrigation intervals 4, 8, and 12 days as control, moderate, extreme) | Under drought stress, the yield of essential oils decreased by 30%, and phenols and nano-silicon increased plant drought tolerance  | [159] |
| <i>Cistus clusii</i> Dunal                                 | Drought stress (days of drought 15, 30, 50)   | Increase phenolics (flavonols, epigallocatechin gallate)  | [160] |
| <i>Crataegus laevigata</i> (Poir.) DC.                     | Drought (water deficit for 10 days vs. watering daily)                                | Increase phenolics (chlorogenic acid, (-)-epicatechin)  | [161] |
| <i>Glycine max</i> (L.) Merr.                              | Drought stress (non-irrigated field)  | Increased alkaloids (trigonelline)  | [162] |
| <i>Hypericum brasiliense</i> Choisy                        | Drought stress (water stress (waterlogging and drought))                              | Increased terpenoids (betulinic acid)   | [163] |
| Pepper ( <i>Capsicum annuum</i> L.)                        | In vitro, supplemented MS with 200 µM CdCl <sub>2</sub>                               | ZnO-NPs induced mitigation of Cd-toxicity by increased activity of enzymatic antioxidants   | [164] |
| Giant Juncao ( <i>Pennisetum giganteum</i> Ten. ex Steud.) | Salt stress (250, 500 mM NaCl)  | Salicylic acid mitigated the adverse impacts of salt stress, which decreased flavonoids by enhancing the content of chlorogenic acid  | [165] |
| <i>Brassica nigra</i> L.                                   | Salt stress (100 and 150 mM NaCl)   | Salinity enhanced forming of many bioactives e.g., phytosterols, and tocopherols  | [166] |
| Faba bean: <i>Vicia faba</i> L.                            | Salt stress at 150 mM NaCl  | Salinity induced accumulation of flavonoids, phenols, and tannins, in response to ZnO-NPs   | [167] |
| <i>Calotropis procera</i> (Aiton)                          | Salt stress in 3 experiments up to 320 mM NaCl using Petri dishes and hydropriming    | Seed priming with thiourea and ascorbic acid increased tolerance to salinity up to 120 mM by increasing phenolic acids (gallic, caffeic, p-coumaric, p-benzoic, and sinapic acid) | [168] |
| Wheat ( <i>Triticum aestivum</i> L.)                       | Salt stress (150 mM)  | Priming with 0.12% Cu-chitosan-NP induced an increase in β-carotenoids, total carotenoids   | [169] |
| <i>Catharanthus roseus</i> (L.) G. Don                     | Cold stress (4 °C) in growth chamber  | Decreased alkaloids (vindoline)   | [170] |
| <i>Glycine max</i> (L.) Merr.                              | Cold stress (10 °C)   | Increased phenolics (genistein, daidzein)   | [171] |
| <i>Solanum Lycopersicon</i> L.                             | Cold stress (6 and 3 °C)  | Increased terpenoids (δ-elemene, α-humulene, and β-caryophyllene)   | [172] |
| <i>Withania somnifera</i> (L.) Dunal                       | Cold stress (4 °C) under controlled environment                                       | Increased terpenoids (withanolide A; withferin A)   | [173] |
| <i>Zea mays</i> L.   | Cold stress (10 °C)   | Increased phenolics (pelargonidin)  | [174] |

### 4.3. Plant Nutrition under Stressful Soil

The relationship between soil and plant is very close due to soil generally being the main growing medium for the plant. The soil and its properties are the main controlling factor in plant growth and development. Any stress on the soil will be also a stress on the cultivated plants that are grown in this soil. The ideal conditions for growing plants in soil include sufficient and proper nutrients for soil fertility, soil aeration, soil health, suitable water irrigation, etc. Stressful soil is soil that has a problem,



stress, or obstacle restricting productivity. A problematic soil could be defined as a soil that has a reason for a restriction on its economical cultivation, but it requires a suitable management. These soils may include greenhouse soil in arid regions, saline/alkaline soil, acidic soil, sandy soil, waterlogged soil, calcareous soil, compacted soil, infertile soil, and eroded soil (Figure 6A,B).



(A)



(B)

**Figure 6.** (A) Desert soils have different problems, which include eroded soil (upper photos), very low vegetation due to stresses (middle photos), and salinization due to very high evaporation rate (lower photos). Different photos from different places in Egypt (Shalateen, Matrouh, and Siwa) are all by El-Ramady. (B) Desert soils have different handling compared to the soils of Delta in Egypt. The upper photos express on salinity and waterlogging problems, whereas the same problems in

soils of Delta in Egypt could be noticed in the middle and lower photos, due to the salinization under high soil water table. Different photos from different places in Egypt (Siwa in upper 2 photos and Kafr El-Sheikh in the rest) are all by El-Ramady.

Abiotic and biotic stressors have a significant impact on the production of major crops all over the world. Extreme abiotic conditions such as high and low temperatures, drought, salinity, osmotic stress, extremes of pH, heavy rains, floods, various pathogens, and frost damage all pose serious hazards to plant growth and crop production [175]. Under these environmental stresses, plants generate higher quantities of the plant hormone ethylene or other bioactives (e.g., melatonin) in response to certain environmental challenges, which largely inhibits plant growth and proliferation until the stress is alleviated by lowering ethylene levels [176]. The role of plant bioactives is distinguished under stressful conditions such as carotenoids, ascorbic acid, and flavonoids, which are considered important antioxidants for scavenging reactive oxygen species (ROS).

Among abiotic stresses, drought and salinity can cause serious damage to global food production. Global soil salinity is one of the most serious environmental stresses in agriculture around the world, converting agronomically useful fields into unproductive areas by 1–2% every year in arid and semi-arid zones. Soil salinization has rendered around 7% of the world's land and 20% of its arable land uninhabitable [177]. Salinity has long been known to hinder the growth and development of most plants, resulting in lower yields. Furthermore, salinity causes significant changes in plant growth and metabolism, i.e., physiological, morphological, and biochemical alterations [178]. Drought is another important abiotic stress that has a negative impact on the development and production of most cultivated agricultural crops, particularly in arid and semi-arid areas. Drought stress, along with climate change, which causes more severe and frequent droughts, is anticipated to produce serious plant growth issues for more than half of arable areas by 2050 [179]. Furthermore, drought stress affects water relations, photosynthetic assimilation, and nutrient uptake in essential field crops, causing severe effects on plant development and metabolic activities. The nutritional imbalance of minerals limits plant growth and development in poor soils rich in nutrients [180].

Soil salinization, competitive ion uptake, and transport or partitioning of ions within the plant are some of the negative consequences of nutritional imbalances, which can occur when a nutrient's physiological role is deactivated, resulting in an increase in the internal plant requirement for that particular essential element [177]. A considerable amount of nutrients are unavailable to plants due to soil binding organic and mineral components and the production of insoluble precipitates. Plant fitness can be harmed by essential element imbalances due to their impacts on plant nutrition and water absorption, as well as their toxic effects on plant cells [181]. Management of stressful soil could be achieved through different approaches such as soil conservation (biological methods including manures, green manure, water hyacinth, and selecting salt-tolerant varieties) and agronomic approaches such as tillage and improving irrigation, drainage, and fertilizers (Figure 7), as reported by [182].



**Figure 7.** Different cases for management of plant nutrition, which include, in the upper photos, using plastic mulching, even in an open field or in a greenhouse; in the middle, collecting the fall leaves from deciduous trees during the autumn to make

compost as an important organic fertilizer; and at the bottom, cultivation of paddy rice under soil salinity as an important strategy to reclaim this soil salinity. All photos from Debrecen (Hungary), Göttingen (Germany), and Kafr El-Sheikh (Egypt) by El-Ramady.

Concerning the impact of abiotic stresses on plant bioactives, many stresses have been presented in **Table 6**, such as drought, salinity, element toxicity, and cold stress. In general, there is no one trend for this relationship, but some stresses increase the content of the bioactives, whereas others do the opposite. For example, some stressful plants tend to increase plant content of bioactives under drought, such as *Cistus clusii* (increased phenolics or flavonols), *Tanacetum parthenium* (decreased phenols), *Crataegus laevigata* *Glycine max*, and *Hypericum brasiliense*, which increased the previous content of phenolics, alkaloids, and terpenoids under drought, respectively. More problematic soils and bioactive compounds and more details on the plant bioactives cultivated as a response to abiotic stress are explained in **Table 6**.

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