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Cobalt in Soil-Plant-Animal and Human Nutrition: A Review

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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Review Article

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Abstract

Cobalt (Co) is a transition metal of increasing environmental and biological significance because of its essential and toxic roles across soil-plant-animal-human systems. This review aims to synthesise the literature on cobalt across the soil-plant-animal-human continuum. Naturally occurring in minerals such as cobaltite and erythrite, its concentration in soils varies widely depending on parent material, climate, and anthropogenic activities, including mining, fertiliser use and industrial waste disposal. Cobalt predominantly exists as Co^{2+} and Co^{3+} in soils, with its solubility, mobility and plant availability strongly influenced by soil pH, redox status and interactions with organic matter. Acidic soils enhance its presence in the soil solution, whereas alkaline conditions reduce availability through precipitation and adsorption.

In plants, cobalt is not universally classified as an essential nutrient; however, it performs important biochemical functions, particularly in nitrogen-fixing legumes. Co supports *Rhizobium* activity,

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leghaemoglobin formation and nitrogenase protection, thereby enhancing biological nitrogen fixation. Low concentrations improve chlorophyll content, urease activity and seed yield, whereas excessive accumulation disrupts iron uptake, impairs chloroplast structure, reduces photosynthesis, and leads to growth inhibition, chlorosis and necrosis.

Animal nutrition is strongly linked to soil and forage cobalt levels. Cobalt is required for ruminal synthesis of vitamin B_{12}, which supports metabolic pathways involving carbohydrate, fatty acid and amino acid metabolism. Deficiency in livestock results in reduced weight gain, anaemia, poor feed utilisation and reproductive impairment, while excess intake may disrupt enzymatic activity and mineral metabolism.

In humans, cobalt functions through vitamin B_{12}, which is essential for DNA synthesis, nervous system health, red blood cell formation and energy metabolism. Deficiency, which is more prevalent among vegetarians and elderly individuals, leads to anaemia and neurological impairment. Conversely, excessive cobalt exposure through contaminated food, water or occupational sources can induce gastrointestinal distress, immune dysfunction, cardiotoxicity and DNA damage.

Overall, this review presents the importance and behaviour of cobalt in soil, plants, animals and humans. Understanding cobalt behaviour in soils and its movement through the food chain is vital for managing deficiency-related disorders while preventing toxicity within interconnected agricultural and ecological systems.

Keywords: Cobalt; beneficial element; bioavailability; nitrogen fixation; enzyme; metabolism.

1. Introduction

Cobalt (Co) is a transition metal positioned in the fourth period and ninth group of the d-block of the periodic table. It was first discovered in 1735 by the Swedish chemist George Brandt. Cobalt is regarded as a beneficial element in the metabolism of all animals, including humans, as well as in prokaryotic organisms. It is an essential component of cobalamin, commonly known as vitamin B12, which is required for the nutrition of both humans and animals. Although Co performs important physiological and biological functions in legumes, it has not been recognised as an essential nutrient for plant growth (Khalid et al., 2023). In leguminous plants, Co is utilised by microorganisms involved in atmospheric nitrogen fixation. It has also been reported to exert beneficial effects on plant growth. Therefore, an adequate supply of Co is important for maintaining normal metabolic activities. However, when present above threshold concentrations, Co can be highly toxic to plant metabolism. Consequently, excessive Co levels in soils may pose a serious threat to plant physiological processes and growth performance. Recent evidence from soybean indicates that seed treatment involving cobalt, along with boron and molybdenum, can influence nodulation, growth, yield attributes and seed quality under field conditions (Bangale et al., 2024).

At elevated concentrations, cobalt can impair the availability of essential nutrients, disturb chloroplast structural integrity, restrict net photosynthetic activity and reduce the activity of iron-containing enzymes. Previous studies have reported various toxicity symptoms associated with Co stress, including leaf chlorosis and suppressed plant growth.Recent wheat-based evidence also indicates that elevated cobalt exposure can suppress growth, induce chlorosis and disturb nutrient movement under stress conditions (Ragab et al., 2025).

Despite its significance, cobalt availability in soils is generally limited and highly variable, depending on factors such as soil type, pH, organic matter content and redox conditions (Kabata-Pendias, 2011). In soils, cobalt occurs mainly as divalent (Co^{2+}) and trivalent (Co^{3+}) ions, with Co^{2+} being more soluble and readily bioavailable. The principal sources of Co in soils include parent rock materials, atmospheric deposition and anthropogenic inputs, such as mining activities, industrial emissions and the use of Co-containing fertilisers and manures (Alloway, 2013). Metal availability in soil and plants significantly influences ruminant and human health. Cobalt is important for several metabolic functions, and its deficiency impairs production and reproduction. Co is required as a nutrient for microorganisms in ruminant animals and thereby aids ruminal synthesis of vitamin B_{12}. The transmission of metals from soil to plants depends on various soil characteristics, such as the presence of organic matter, clay content, soil acidity or alkalinity, and the category of metal (Aboubakar et al., 2023). Cobalt (Co) is important for animals and humans. Vitamin B_{12} is an important micronutrient among all vitamins, as it has a considerable effect on various bodily functions (Patel et al., 2022), *viz.*, RBC formation in bone marrow, DNA synthesis, nervous system health, fatty acid metabolism, activation of folate and formation of haemoglobin. As metals enter plants through any route, they begin to accumulate in plant tissues. Higher levels can disturb various vital physiological activities and negatively affect nutritional quality. Co and its compounds play an essential role in humans, as they are the central atoms of cobalamin, a co-enzyme precursor whose absence causes anaemia.

Recent synthesis further suggests that soils and terrestrial plants contribute to cobalt and cobalamin supply in terrestrial organisms, although information on soil cobalamin remains limited (Jörgensen & Joergensen, 2024).

Cobalt enters the soil environment through various sources, including the application of phosphate fertilisers, industrial wastewater and sewage sludge. In legumes, Co is primarily required for rhizobia-mediated nitrogen fixation (Kafeel et al., 2023; Hu et al., 2021). It enhances the activity of nitrate reductase and dehydrogenase enzymes involved in atmospheric nitrogen fixation through the formation of leghaemoglobin; in the absence of Co, microorganisms are unable to carry out nitrogen fixation effectively. However, Co has been reported to adversely affect plant physiological processes when supplied at both excessive and deficient levels. Cobalt toxicity inhibits the electron transport chain of photosystem II (PSII). Plants exhibit symptoms of Co toxicity when Co concentrations exceed 6 ppm. Furthermore, Co bioaccumulation can reduce plant biomass, nutrient uptake, growth and protein content (Ozfidan-Konakci et al., 2022; Salam et al., 2022). A recent review of heavy-metal contamination in drinking water identifies cobalt among metals for which toxicity depends on concentration, exposure duration and route of exposure (Lubal, 2024).

Imbalanced metal concentrations in animal diets also affect livestock production. McDowell et al. (1983) reported that when feed contains less than 0.07 mg/kg Co, animals develop deficiency. An insufficient amount of cobalt in animal diets causes vitamin B_{12} deficiency, reduced body weight, poor growth and impaired reproductive function (González-Montaña et al*.,* 2020).

Considering the beneficial and toxic roles of Co in plant biochemistry, as well as its necessary functions and deficiency effects in animals and humans, it is important to understand environmental levels of Co and its behaviour in the soil-plant-animal-human system.

Research gap: Although the literature describes cobalt deficiency and toxicity in separate soil, plant, animal and human contexts, a concise synthesis linking soil behaviour, plant uptake, animal nutrition and human exposure within one continuum remains necessary.

Objective: This review aims to synthesise cobalt behaviour and its nutritional and toxicological significance across soil, plant, animal and human systems.

2. Cobalt in Soils

Cobalt is a naturally occurring trace element in the transition series. In nature, it does not occur in its native form and is most often found in minerals such as sulphides, oxides and hydrates, *viz.*, erythrite [$Co_3(AsO_4)_2.8H_2O$], cobaltite (CoAsS), linnealite (Co_3S_4), smaltite [$Co(Ni)As_3$], safflorite ($CoAs_2$) and spherocobaltite ($CoCO_3$) (Shahid, 2017). The concentration of cobalt in soil depends on soil-forming processes; therefore, its range varies under different agroclimatic conditions. It is generally greater in saline soils of warm, dry climates. The average total Co content in the earth's crust is 40 mg kg^{-1} (Rudnick & Gao, 2003). The concentration of cobalt in soil broadly ranges from 0.1 to 100 mg kg^{-1}, whereas the average cobalt content in soils worldwide is 8 mg kg^{-1}. In soils such as sandy podsols, it averages 5.5 mg kg^{-1}, while organic soils average 4.4 mg kg^{-1}. The highest values for dark brown clay soils and limestone soils are 10-12 mg kg^{-1} (Barałkiewicz & Siepak, 1999). The concentration of cobalt reported from different soils worldwide varies, for example, 16.5-26.8 mg/kg in Egyptian soils, 116 mg kg^{-1} in Japanese soils and 122 mg kg^{-1} in Australian ferralsols (Rawat et al*.,* 2019).

The normal distribution of cobalt in Indian agricultural soils ranges from 1 mg kg^{-1} to 17 mg kg^{-1} (Krishna & Govil, 2005). Different states of India have reported different ranges of cobalt concentrations depending on local geology and soil type.

The maximum permissible allowable limit for soils is 50 mg kg^{-1} (Khalid et al*.,* 2023). Values above the permissible limit may be due to anthropogenic activities such as fertiliser and soil amendment application, industrial emissions from mining, smelting and metal refining, battery effluents and urban waste.

Table 1. Distribution of cobalt in mg kg^{-1} in different Indian agricultural soils

Location	Cobalt content	Reference
Maharashtra	0.02-1.8	Debbarma et al., 2014
Punjab	0.49-14.2	Verma et al., 2021
	0.13-19.28	Daulta et al., 2023
Haryana	5.1-12.9	Daulta et al., 2023
Delhi	1.88	Rani et al., 2021
Uttar Pradesh	0.01-19.28	Daulta et al., 2023

Cobalt may occur at oxidation states from -1 to +4, but in nature it usually occurs as a divalent cation. Of the total Co, more than 95% does not move and remains in the soil. In soil, Co is found in soluble and exchangeable forms, bound to carbonate, bound to organic matter, bound to oxides and hydroxides, and in primary and secondary minerals. The most frequent forms of Co in soil are Co^{2+} (ionic), Co^{3+} (coordination-forming compound), $CoOH^{+}$, $Co(OH)^{3}$- and readily soluble $Co(OH)_2$ (Kosiorek & Wyszkowski, 2019).

Table 2. Availability of cobalt with change in Ph

pH	Dominant form	Availability
3-5	Soluble & exchangeable Co^{2+}	Highly mobile &plant available
6-7	Adsorbed cobalt (surface adsorption)	Moderately mobile
>7	Precipitated/ solid Co minerals	Low mobility- precipitation dominates
Acidic, neutral & Alkaline	Complexion with organic matter	More mobile at neutral – alkaline pH

[References: Sparks (2003) and Lindsay (1979)]

In acidic soil, cobalt is mainly present in the divalent form (Co^{2+}), which is relatively soluble and readily available to plants. Low pH increases the dissolution of cobalt-containing minerals, reduces adsorption on soil colloids and enhances cobalt concentration in the soil solution. In strongly acidic soils, oxidation of Co^{2+} to Co^{3+} may occur, often mediated by manganese oxides and microorganisms, leading to reduced availability. In alkaline soil, cobalt readily reacts with hydroxyl ions to form insoluble cobalt hydroxide [$Co(OH)_2$] and may also associate with carbonates, leading to precipitation. Additionally, cobalt ions are strongly adsorbed onto clay minerals and iron and manganese oxides, which decreases their presence in the soil solution.

Bahnasawy et al. (2019) reported that the soluble, exchangeable, carbonate-bound, Fe–Mn-bound and organic-bound fractions of Co ranged from 1.38 to 4.23%, 5.26 to 45.58%, 1.79 to 7.34%, 2.63 to 7.75% and 2.29 to 9.52%, respectively. Their findings further indicated that the distribution of Co among the different soil fractions followed the order: residual > exchangeable > organic-bound > Fe–Mn-bound > carbonate-bound > soluble. In submerged soils, cobalt behaviour is strongly influenced by redox potential. It competes with other cations such as Fe^{2+}, Mn^{2+}, Zn^{2+}, Na^{+} and Ca^{2+} for exchange sites.

In nature, isotopes such as ^{55}Co, ^{56}Co, ^{57}Co, ^{58}Co and ^{60}Co also exist due to human activities (Tappero et al., 2007). Apart from its presence in soil, Co is also present in atmospheric air in oxidised and insoluble forms at 0.0005 to 0.005 mg dm^{-3}.

Chemical speciation (oxidation forms) of metals in soil governs their biological behaviour in the soil-plant continuum and is a better indicator of mobility, phytoavailability and translocation in plants (Khalid et al., 2023).

3. Cobalt in Plant

Cobalt is a trace element involved in the growth and development of plants. Plants contain Co at concentrations of 0.1 to 10 mg kg^{-1} dry weight. Co is absorbed by plant roots in divalent (Co^{2+}) and trivalent cationic forms. Plant absorption of Co is influenced by complexation with organic and inorganic ligands and by chemical speciation (Khalid et al., 2023). Co mostly accumulates in plant roots, but free Co ions are transported towards the aerial parts of plants. Co is essential for the synthesis of cobalamin (vitamin B_{12}) by nitrogen-fixing bacteria in leguminous root nodules. In *Rhizobium* bacteria, cobalt, in the form of cyanocobalamin, is required for leghaemoglobin synthesis. Leghaemoglobin regulates the activity of three enzymes associated with root nodule function: (1) methionine synthase, which influences bacteroid size and protein synthesis; (2) ribonucleotide reductase, which is involved in DNA synthesis and cell division in *Rhizobium* (Chatel et al., 1978); and (3) methylmalonyl-CoA mutase, which is associated with leghaemoglobin synthesis (Das, 2000; Ali et al., 2010).Co present in smaller quantities increases leghaemoglobin content in plants (Onte et al., 2022). Leghaemoglobin synthesis is impaired directly under cobalt deficiency, ultimately affecting the N-fixing capacity of plants. This occurs because nitrogenase is protected by leghaemoglobin from exposure to oxygen (Hopkins, 1995). In small quantities, cobalt increases urease enzyme activity (Rod et al., 2019), chlorophyll content and nitrogenase activities in soil and plants (Lavres et al., 2016).

However, to satisfy nutritional requirements, the cobalt concentration in plant tissues should not fall below 0.08 mg kg^{-1}. Among papilionaceous plants, clovers possess the greatest capacity for Co accumulation, while among cereals, wheat shows the highest accumulation potential. Among vegetables, cabbage and lettuce are reported to contain the highest cobalt concentrations (Nirmal-Kumar et al., 2007). The application of various soil sorbents, such as manure and calcium oxide, has been shown to mitigate the adverse effects of cobalt contamination on plants (Kosiorek & Wyszkowski, 2019). In higher plants, Co is reported to bind strongly to roots and is primarily absorbed from the soil solution through passive transport. Owing to its close chemical similarity with nickel (Ni), it may be inferred that both elements enter plant cells through the same plasma membrane carriers. Gad (2006), in a study on pea plants (*Pisum sativum* L.), reported that the application of 8 ppm Co to soil enhanced plant growth, nodule number and weight, nutrient status, seed-pod yield and seed quality. These improvements were most likely associated with the essential role of Co in symbiotic rhizobia inhabiting the nodules of leguminous plants.

Palit et al. (1994) reported that the beneficial effects of Co include delayed leaf senescence through the inhibition of ethylene biosynthesis, as well as improved drought resistance in seeds. Cobalt has also been shown to stimulate the accumulation of isoquinoline, an alkaloid, in medicinal plants by upregulating the biosynthesis of aromatic amino acid precursors involved in alkaloid formation.

When cobalt concentrations exceed threshold levels, iron assimilation is inhibited, resulting in toxicity symptoms, suppression of growth processes and the development of disorders such as chlorosis, necrosis and tissue death. Excess Co also disrupts photosynthesis, reduces intercellular spaces and causes the degradation of chloroplast structure (Chatterjee & Chatterjee, 2002; Chaudhari et al., 2017; Kosiorek & Wyszkowski, 2019). It may also reduce seed quantity and quality, while substantially impairing the synthesis of sugars, proteins and starch. The activities of certain enzymes, including peroxidase and acid phosphatase, have been reported to increase under Co stress (Chatterjee et al., 2006). Plants accumulating higher concentrations of Co generally exhibit reduced Fe content, protein concentration, chlorophyll content and catalase (CAT) activity in their leaves. Elevated Co concentrations also adversely affect root growth by inhibiting cell division and limiting nutrient and water uptake (Khalid et al., 2023). In cauliflower leaves, Co phytotoxicity has been shown to restrict enzymatic activity, protein synthesis and chlorophyll biosynthesis, as well as reduce the root-to-shoot translocation of Ca, Mg, Fe and P (Li et al., 2009).

Gopal et al. (2003) conducted an experiment on tomato plants to assess the effects of different cobalt concentrations. They reported a substantial reduction in plant biomass when Co was supplied at concentrations ranging from 0.05 to 0.5 mM. The greatest decline in biomass occurred at 0.5 mM Co, resulting in an approximately 85% reduction in the biomass of treated plants. Basu et al. (2008) observed that the nutrient content of groundnut kernels increased at a lower cobalt dose of 0.21 kg ha^{-1}, whereas a higher dose of 0.42 kg ha^{-1} reduced the concentrations of N, P and K. Similar findings on the influence of inoculants and cobalt on nutrient concentration were also reported by Jana and Sounda (1994) and Mehta (1996).

4. Cobalt in Animal

Microminerals do not yield energy, but they play important roles in many activities in the body (Soetan et al., 2010). Mineral nutrients are important for several metabolic functions, and their deficiency impairs production and reproduction. Cobalt is essential for animal nutrition, and animal requirements should be met through feeding practices because the body cannot synthesise it. The requirement for Co is around 0.11 ppm (mg kg^{-1}) dry matter in the diet. The recommended Co level for beef cattle is 0.15 mg kg^{-1} dry matter (National Academies of Sciences, Engineering, and Medicine, 2016). Co is required as a nutrient for microorganisms in ruminant animals and thereby aids ruminal synthesis of vitamin B_{12}. It influences energy metabolism by facilitating glucose formation in dairy animals (Hu et al., 2021). Vitamin B_{12} is an essential part of two enzymatic systems involved in the metabolism of carbohydrates, lipids, some amino acids and DNA. Adenosylcobalamin and methylcobalamin are coenzymes of methylmalonyl coenzyme A (CoA) mutase and methionine synthetase and are essential for obtaining energy through ruminal metabolism. Cobalamin-dependent enzymes that participate in metabolic pathways are: (1) methionine synthase, which synthesises methionine from homocysteine and supports protein metabolism and RBC formation; (2) methyltransferase, which transfers methyl groups from different methyl donors to acceptor molecules and supports methylation metabolism; (3) ribonucleotide reductase, which catalyses the production of deoxyribonucleotides needed for nucleotide synthesis and DNA synthesis; and (4) methylmalonyl-CoA mutase, which synthesises succinyl-CoA from methylmalonyl-CoA and supports gluconeogenesis and the TCA cycle (Hu et al., 2021). The youngest animals have the highest requirement for this element, whereas older animals have a lower cobalt requirement; however, cobalt content rises over time as a result of accumulation (Kosiorek & Wyszkowski, 2019). Both deficiency and excess of cobalt can result in disease symptoms.

There is a complex relationship between soil, plants and animals due to specific plant characteristics and interactions among different minerals. Mineral-deficient soils appear to play a definitive role in causing deficient levels in rations (McDowell et al., 1983; Singare et al., 2019). Despite the large cattle population, milk production is low owing to poor individual cow productivity, which is attributed to malnourishment and mineral deficiency (Sharma et al., 2003). Cattle feeding on low concentrations of cobalt may also develop Co deficiency (Silva et al., 2020). Dairy cattle reared under smallholder production systems are deficient in most minerals (Kumaresan et al., 2010).

The earliest indication of cobalt deficiency is the inability of ruminal microorganisms to convert succinate into propionate (Kennedy et al., 1991). Initial symptoms of Co deficiency include anorexia, moderate weight loss and poor growth performance. As the deficiency becomes more severe, cattle may develop rapid weight loss, fatty liver and pallor of the mucous membranes, indicating anaemia (National Academies of Sciences, Engineering, and Medicine, 2016), along with reduced weight gain and increased mortality among offspring. Young cattle are regarded as more susceptible to Co deficiency (Constable et al., 2017). An excessively low dietary cobalt supply can cause anaemia and reduce plasma homocysteine concentrations in these animals (Stangl et al., 2000; Taugbol et al., 2010; Vellema et al., 1999; Valli et al., 2016). Additional symptoms include wool discolouration and characteristic discharge from the ears and eyes (Kosiorek & Wyszkowski, 2019). Conversely, excessively high cobalt concentrations in the blood of dairy cows may reduce the levels of fatty acid desaturation products in milk and blood. Excess Co may also restrict the transport of divalent metals, such as iron and zinc, to the udder and disturb enzymatic activity in mammary gland cells (Taugbol et al., 2010). Silva et al. (2020) reported a positive response in alleviating symptoms associated with Co deficiency in cattle through oral cobalt and vitamin B12 treatment, together with mineral supplementation.

5. Cobalt in Human

Cobalt performs an important role in the production of vitamin B_{12} in humans. Vitamin B_{12} is an important micronutrient among all vitamins, as it has a considerable effect on various bodily functions (Patel et al., 2022). Cobalt intake by humans varies between 5 and 50 ug day^{-1} and is mainly in the form of inorganic Co. The maximum Co intake up to 1800 umol does not cause any negative effect. Co plays an important role in RBC formation in bone marrow, DNA synthesis, nervous system health, fatty acid metabolism, activation of folate and formation of haemoglobin. Deficiency in the human body leads to anaemia, resulting from a low amount of produced vitamin B_{12}. The occurrence of vitamin B_{12} deficiency is much higher in vegetarians than in non-vegetarians (Vora et al., 2017; Gupta et al., 2016; Patel et al., 2022). Mild cobalamin deficiency is most common in elderly white men and least common in Black, Asian and American women (Carmel et al., 2002; Patel et al., 2022). Several studies have shown that long-term use of medications such as antacids, chronic alcoholism and smoking is associated with vitamin B_{12} deficiency. Khan et al. (2017), Arora et al. (2016) and Singh et al. (2016) concluded that vitamin B_{12} deficiency was significantly higher among patients who smoked than among those who did not. The longer the duration of RO water consumption, the greater the possibility of developing vitamin B_{12} deficiency (Gupta et al., 2016; Patel et al., 2022). Excess concentrations of Co can cause hyperglycaemia, gastric disturbance and polycythaemia, and may lead to reproductive changes. Exposure to excess cobalt results in headache, high or low blood pressure, diarrhoea and frequent vomiting. High Co concentrations also affect the immunological system (Świątkowska et al., 2023; Garcia et al., 2020; Domingo, 1989). Cobalt can also mediate significant allergenic problems, interstitial lung disease, asthma and alveolitis (Domingo, 1989). Tools containing cobalt admixtures and cobalt presence in industrial plants can induce allergic reactions on the skin and hands. The harmful effects of Co on humans are mainly due to intake of Co-contaminated water and food. Another consequence of exposure to cobalt above permissible levels is DNA damage and interference with DNA repair mechanisms. Cobalt toxicity is intensified in the presence of iron, with which it shares similar atomic properties (Ryuko et al., 2012). In the presence of H_2O_2, cobalt has been shown to induce alterations in chromatin DNA isolated from cultured human cells (Nackerdien, 1991).

The harmful effects of cobalt in the human body are also associated with radiation emitted by its isotopes, which may cause various short- and long-term diseases. Excessive accumulation of cobalt isotopes can also increase the risk of cancer (Bezerra et al., 2014).

6. Conclusion

Cobalt is an important trace element within the soil-plant-animal-human continuum. Its behaviour in soil is controlled by soil pH, redox conditions, organic matter, clay minerals, oxides, parent material and anthropogenic inputs. These factors determine cobalt solubility, mobility and availability to plants. Although cobalt is not universally classified as an essential nutrient for higher plants, it has beneficial functions, particularly in leguminous crops, where it supports symbiotic nitrogen fixation through its role in cobalamin-dependent microbial processes and leghaemoglobin formation. At suitable concentrations, cobalt may improve plant metabolism and productivity, but excessive accumulation can reduce nutrient uptake, damage chloroplasts, suppress photosynthesis and impair growth.

In animal nutrition, cobalt is required for ruminal synthesis of vitamin B_{12} and is therefore important for energy metabolism, growth, reproduction and overall productivity. Deficiency may lead to anaemia, poor growth, impaired reproduction and reduced performance, while excess cobalt can disturb mineral metabolism and enzymatic functions. In humans, cobalt is biologically relevant mainly as a component of vitamin B_{12}, which is essential for red blood cell formation, DNA synthesis and nervous system function. Safe cobalt management requires maintaining adequate levels while avoiding contamination and toxicity.

7. Limitations

This review has some limitations. It is based on previously published literature and does not include new experimental data. The manuscript presents a broad discussion of cobalt across soil, plant, animal and human systems, but it does not follow a systematic review method with defined search databases, search terms, screening criteria or quality assessment of selected studies. Therefore, the coverage of literature may not be exhaustive. Some reported cobalt concentration ranges, threshold values and toxicity limits vary among soil types, plant species, animal categories and exposure conditions and should be interpreted with caution. The review also includes information from different geographic regions and production systems, which may limit direct applicability to specific local agricultural conditions. In addition, the human nutrition and toxicity sections are summarised broadly and require careful interpretation because cobalt effects depend on chemical form, dose, exposure duration and route of intake.

Declaration of AI Use

This manuscript was prepared through the combined contributions of all author(s), including contributions to the study design, data, content development, results, interpretation, and related scholarly work. The author(s) acknowledge the use of Grammarly and ChatGPT to assist with grammar checking, language refinement, reference formatting. These AI-assisted tools were not used as authors and did not replace the intellectual contributions or scholarly judgment of the author(s). All AI-assisted outputs, including content, references, and interpretations, were carefully reviewed, revised, verified, and approved by the author(s). The author(s) accept full responsibility for the accuracy, integrity, and final content of the manuscript.

Competing Interests

Authors have declared that they have no known competing financial interests or non-financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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