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Review

Copper Pollution in Agricultural Soils: A Bibliometric Analysis and PRISMA-Guided Systematic Review of Sources, Environmental Impacts, and Remediation

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Abstract

Copper (Cu) accumulation in agricultural soils, resulting from various anthropogenic inputs, can adversely affect soil properties, crop productivity, and environmental quality. Effective monitoring and sustainable remediation are therefore important for managing contaminated soils. This review combines systematic bibliometric analysis with qualitative thematic synthesis to examine research on Cu pollution in agricultural soils. The literature was retrieved from Scopus and Web of Science and screened according to the PRISMA guidelines. Following duplicate removal and eligibility assessment, the final dataset comprised 726 publications covering the period 1988–2025. Bibliometric and thematic analyses were used to identify publication trends and seven major research areas addressing Cu sources and occurrence, analytical methods, environmental and biological effects, co-contamination, and remediation. The bibliometric results revealed a geographically diverse research field dominated by environmental and agricultural sciences, with prominent themes including Cu contamination, metal interactions, ecological effects, crop uptake, and remediation. The qualitative synthesis indicates that Cu accumulation can alter soil microbial communities and nutrient cycling and impair crop growth, although the magnitude of these effects depends on soil conditions, Cu availability, and exposure levels. Immobilisation, biochar, phytoremediation, microbial-assisted approaches, and advanced monitoring technologies have shown potential for managing Cu-contaminated soils. Their effectiveness depends on site conditions and the endpoints used to assess remediation. Sustainable management requires source-specific monitoring, appropriate environmental and exposure-risk assessment, and integrated remediation strategies supported by long-term field research.

Keywords: copper; copper contamination; agricultural soils; copper-based fungicides; copper bioavailability; bibliometric analysis; soil microbial communities; biochar; immobilization; phytoremediation; ecological risk assessment; food-chain contamination; sustainable soil remediation

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1. Introduction

Copper (Cu) is an essential micronutrient for plants and other living organisms, where it participates in photosynthesis, respiration, electron transport, and the activity of numerous enzymes. However, the beneficial effects of Cu depend on its concentration, as excessive levels can induce oxidative stress and toxicity [1–4]. As a naturally occurring component of the Earth's crust, Cu occurs in soils at variable concentrations depending on parent material, soil-forming processes, and environmental conditions. Copper-based fungicides have been widely used to control fungal and bacterial diseases in agricultural crops, particularly in viticulture and other perennial cropping systems. Their repeated application can contribute to the long-term accumulation of Cu in surface soils because Cu is not degraded and its persistence depends on soil properties and environmental processes [5–7].

The environmental behavior of Cu in soil is strongly influenced by its chemical form and interactions with soil components. Copper may occur in the soil solution, on exchange sites, associated with iron (Fe), aluminum (Al), and manganese (Mn) oxides, incorporated into the crystal lattice of primary and secondary minerals, or bound to soil organic matter and living organisms [8,9]. The source of Cu contamination and the duration of exposure can modify its distribution among different soil geochemical fractions, consequently affecting its mobility and bioavailability [10,11]. These processes are particularly important in agricultural systems because Cu accumulation can persist for long periods and may progressively alter soil chemical and biological properties.

Although Cu is required for several essential biochemical functions, excessive concentrations can produce toxic effects on soil organisms, plants, and aquatic systems. Copper serves as a cofactor in several enzymes involved in microbial metabolism. However, excessive Cu concentrations can disrupt microbial physiological processes, alter microbial community composition and diversity, and reduce the activities of soil enzymes involved in nutrient cycling and organic matter decomposition [12–14]. The magnitude of these effects depends on Cu concentration, chemical speciation, soil pH, organic matter content, exposure duration, and the sensitivity of the organisms concerned.

Agricultural practices constitute an important pathway through which Cu enters both soils and adjacent water systems. Repeated applications of copper-based fungicides and pesticides can result in the accumulation of residues in agricultural soils. Prolonged Cu accumulation may contribute to soil degradation, phytotoxicity, alterations in microbial functions, and reductions in soil fertility. Copper-contaminated soils exhibit reduced aggregate stability, making them more susceptible to erosion and compaction [15]. It may also increase the potential transport of Cu from contaminated soils to surface water and groundwater. Soil fauna can be particularly vulnerable to persistent Cu inputs. Repeated Cu inputs from fungicide applications may adversely affect soil fauna, including earthworms, although the magnitude of the response depends on Cu exposure, soil conditions, and species-specific sensitivity [16]. Because earthworms play important roles in soil structure, organic matter turnover, and nutrient cycling, their decline may further influence soil functioning.

Copper contamination can also directly affect plant growth and productivity. Excessive Cu concentrations can inhibit root elongation, impair membrane integrity, induce oxidative stress, and interfere with nutrient uptake in plants, with the severity of these effects depending on plant species, Cu availability, and soil conditions [17–20]. These responses may reduce plant growth and productivity, particularly when Cu exposure exceeds the tolerance limits of the crop concerned. Copper interactions with other soil constituents contribute to these effects. In soil, Cu can bind strongly to organic matter, clay minerals, and hydrated oxides of Fe, Al, and Mn [21]. Such interactions may alter the distribution and availability of essential elements and potentially reduce their availability for plant

uptake. At the same time, Cu transported through contaminated soils may represent a risk to groundwater quality.

The implications of agricultural Cu contamination extend beyond soil processes and plant production because Cu can enter food chains through contaminated crops and other environmental pathways. Elevated Cu exposure has been associated with adverse effects on human health, including potential effects on the liver and kidneys. People with Wilson's disease, an inherited disorder of copper excretion, are especially sensitive to Cu intake [22,23]. Nevertheless, the dietary health risk associated with Cu has been considered relatively low under many conditions because Cu does not bioaccumulate extensively in the human body and because phytotoxic effects may occur at concentrations that limit plant accumulation [24]. The evaluation of soil contamination and its implications for human health requires an integrated assessment of contaminant concentrations, environmental availability, exposure pathways, and the characteristics of potentially exposed populations. Soil-related health risks may arise through direct soil contact, incidental ingestion, inhalation of contaminated dust, and the consumption of crops grown in contaminated soils. However, the presence of a contaminant does not, by itself, demonstrate that harmful exposure has occurred. Risk characterization should therefore combine environmental measurements with evidence concerning contaminant transfer and actual or estimated exposure [25]. The assessment of risk therefore requires consideration of Cu concentration, chemical speciation, soil properties, plant uptake, exposure pathways, and the duration of contamination rather than total Cu concentration alone.

Understanding the fate, mobility, and bioavailability of Cu in agricultural soils is consequently essential for evaluating contamination risks and selecting appropriate management strategies. Traditional approaches for investigating Cu behavior include mass-balance calculations and sequential extraction procedures, which provide information about the distribution of Cu among different soil fractions. More recently, stable Cu isotope analysis based on the $^{65}Cu/^{63}Cu$ ratio has emerged as a complementary approach for investigating the sources, fate, and transport of anthropogenic Cu in environmental systems [25,26]. Such approaches can improve the identification of Cu sources and provide additional information about processes controlling its environmental behavior.

The increasing occurrence of Cu accumulation in agricultural soils has stimulated the development of remediation and risk-reduction strategies. When excessive Cu concentrations occur in agricultural soils and plants, reducing Cu availability and uptake becomes important for maintaining safe crop production. Remediation approaches may be implemented through in-situ or ex-situ techniques depending on contamination intensity, soil characteristics, land use, and economic considerations [27]. Among the available approaches, immobilization and phytoremediation have received considerable attention as potentially effective methods for rehabilitating Cu-contaminated soils and reducing the environmental risks associated with heavy metals [28].

Phytoremediation includes several plant-based strategies, particularly phytoextraction and phytostabilisation. Phytoextraction involves cultivating plants capable of taking up Cu and concentrating it in harvestable tissues, which are subsequently removed from the contaminated site. The approach can be particularly useful for soils with relatively low or moderate levels of contamination because very high metal concentrations may restrict plant growth and limit remediation efficiency [29]. The use of metal-tolerant or hyperaccumulating plants can increase the efficiency of Cu removal from contaminated soils [30]. In contrast, phytostabilisation aims to reduce the mobility and bioavailability of Cu by retaining or immobilizing the metal within the soil–root system rather than removing it from the site [29].

Soil amendments represent another important strategy for reducing Cu mobility and plant availability. Materials such as clays, carbonates, phosphates, and iron oxides have been investigated for their capacity to stabilize Cu in contaminated soils. These amendments can promote the formation or precipitation of relatively stable Cu carbonates and oxyhydroxides or facilitate the formation of cation–anion complexes on the surfaces of Fe and Al oxyhydroxides, thereby reducing the fraction of Cu available for plant uptake [31]. The effectiveness of such approaches depends on soil characteristics, amendment properties, Cu concentration and speciation, and environmental conditions. Consequently, remediation should be considered within the broader context of soil chemistry, biological processes, crop production, and long-term environmental sustainability.

Several review articles have previously examined agricultural soil contamination [32,33], while other reviews have focused specifically on Cu in soils or plants [34–36]. These publications provide important background on soil contamination and the environmental behavior and biological effects of Cu. However, their thematic scope differs from that of the present review. Reviews addressing agricultural soil contamination provide a broader perspective on contaminant sources and impacts, whereas studies focusing specifically on Cu in soils or plants address particular aspects of its occurrence, behavior, or biological effects. The present review builds on these contributions by examining Cu pollution specifically in agricultural soils and integrating its sources and accumulation pathways with soil geochemical processes, mobility and bioavailability, effects on soil organisms and plants, implications for water quality and agricultural productivity, and remediation options. Particular attention is given to the relationships between Cu inputs, soil properties, biological responses, and remediation effectiveness, as well as to the implications of persistent Cu accumulation for long-term agricultural sustainability. This integrated perspective is intended to complement previous reviews by connecting the environmental behavior of Cu with its ecological consequences and the practical management of contaminated agricultural soils.

Therefore, this review aims to provide an integrated assessment of Cu pollution in agricultural soils, with particular emphasis on (i) the major natural and anthropogenic sources and pathways of Cu accumulation; (ii) the occurrence, speciation, mobility, and bioavailability of Cu in agricultural soils; (iii) the effects of Cu contamination on soil properties, microorganisms, soil fauna, plants, and water quality; (iv) the potential implications for agricultural productivity and environmental and human health; (v) current in-situ and ex-situ remediation approaches, including immobilization, phytoremediation, phytoextraction, phyto-stabilization, and soil amendments; and (vi) emerging approaches and research priorities for the sustainable management of Cu-contaminated agricultural soils. By bringing these aspects together, the review seeks to identify the principal mechanisms controlling Cu persistence and risk in agricultural systems and to highlight promising directions for future research and remediation practices.

2. Materials and Methods

This review employed a mixed-methods approach integrating systematic bibliometric analysis with qualitative thematic synthesis to examine the scientific literature concerning copper (Cu) pollution in agricultural soils. The methodological framework was designed to identify publication trends, research hotspots, geographic patterns, major scientific developments, and emerging research themes related to Cu accumulation, mobility, toxicity, and management in agricultural ecosystems while ensuring transparency and reproducibility.

2.1. Bibliometric Assessment

2.1.1. Literature Search Strategy

A systematic literature search was conducted using two internationally recognized scientific databases: Scopus and the Science Citation Index Expanded (SCI-Expanded) available through the Web of Science (WoS) platform. These databases were selected due to their extensive coverage of peer-reviewed literature in environmental sciences, soil science, agricultural sciences, ecotoxicology, pollution studies, and sustainable land management.

The search focused on publications addressing copper contamination, accumulation, and environmental impacts in agricultural soils. Core search terms included combinations of "copper pollution", "copper contamination", "copper accumulation", and "agricultural soils". To broaden the scope and capture related studies, additional keywords included copper toxicity, heavy metals, trace metals, soil contamination, metal mobility, soil–plant interactions, crop uptake, phytotoxicity, bioavailability, soil remediation, risk assessment, agricultural ecosystems, and sustainable management practices.

The literature search and study-selection process followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 framework [37]. Searches were conducted in Scopus and the Science Citation Index Expanded (SCI-Expanded) through the Web of Science (WoS) platform, with the search completed on 20 May 2026. No publication-year limits were applied during retrieval; therefore, the search covered all records indexed by the selected databases up to the search end date. The time intervals shown in Schematic presentation of the workflowrepresent the distribution of publications by publication year and were used for descriptive analysis rather than as eligibility restrictions.

The database-specific search strings are reported in Section 2.1.2 to facilitate reproducibility. The searches were conducted on 20 May 2026, without publication-year restrictions, using Scopus and the Web of Science Core Collection (SCI-Expanded). The initial searches retrieved 624 records from Scopus and 353 records from WoS SCI-Expanded before deduplication. Because some broad search terms may retrieve records that mention metals without specifically investigating copper, topical relevance was assessed during title and abstract screening and subsequently verified through full-text assessment.

2.1.2. Search Syntax

To facilitate reproducibility, the exact search strings used in the two databases are provided below. Searches were performed on 20 May 2026, without publication-year restrictions or additional document-type filters at the retrieval stage.

Scopus (Advanced Search; TITLE-ABS-KEY fields):

TITLE-ABS-KEY ((“agricultural soil*” OR cropland* OR farmland* OR “cultivated soil*” OR “agricultural land*”) AND (“copper pollution” OR “copper contamination” OR “copper accumulation” OR “copper content” OR “copper concentration” OR “Cu concentration” OR “copper toxicity” OR “copper bioavailability” OR “copper mobility” OR “copper remediation”))

Web of Science Core Collection—SCI-Expanded (Advanced Search; Topic field):

TS = ((“agricultural soil*” OR cropland* OR farmland* OR “cultivated soil*” OR “agricultural land*”) AND (“copper pollution” OR “copper contamination” OR “copper accumulation” OR “copper content” OR “copper concentration” OR “Cu concentration” OR “copper toxicity” OR “copper bioavailability” OR “copper mobility” OR “copper remediation”))

The search strings were harmonized to use equivalent concepts and Boolean logic across both databases, with database-specific field syntax. The search terms explicitly combine agricultural-soil contexts with copper-specific concepts to reduce the retrieval of records addressing unrelated metal contamination. Wildcards were used to capture

lexical variations where appropriate. The searches retrieved 624 records from Scopus and 353 records from WoS SCI-Expanded before deduplication. Records were exported for subsequent deduplication, screening, eligibility assessment, and bibliometric processing. Although the search strategy was designed to identify studies specifically addressing copper in agricultural soils, the relevance of individual records was confirmed during screening and full-text assessment.

The searches were executed directly in the respective database platforms using the fields and Boolean operators specified above. The search date, database coverage, applied filters, and retrieved record counts were documented for each database. The search results were exported from Scopus and the WoS Core Collection for subsequent screening, deduplication, and bibliometric processing. No publication-year filter was applied. Because broad metal-related terms could retrieve studies in which copper was not the principal subject, topical relevance was established during title and abstract screening and verified during full-text assessment. For reproducibility, the final search date and the number of records retrieved from each database before deduplication should be reported as follows: Scopus $n = 624$; WoS SCI-Expanded $n = 353$.

2.1.3. Search Limits and Eligibility

No publication-year restrictions were applied during database retrieval. The searches included records indexed in Scopus and the WoS Core Collection (SCI-Expanded) up to 20 May 2026. Publications written in English were considered. Eligible publication types included peer-reviewed research articles, review articles, proceedings papers, and book chapters for which publication type, peer-review status, and topical relevance could be established. Conference abstracts were considered eligible only when they met the prespecified publication-type and peer-review requirements.

Editorials, theses, dissertations, and other non-peer-reviewed publications were excluded. Eligibility was determined according to publication type, language, methodological transparency, and relevance to copper pollution in agricultural soils. Studies were considered relevant when they investigated copper sources, accumulation, distribution, mobility, bioavailability, toxicity, crop uptake, ecological risks, or remediation in agricultural soils or terrestrial farming systems. Records that mentioned copper only incidentally or did not substantively investigate copper-related processes in agricultural soils were excluded.

2.1.4. Data Cleaning and De-Duplication

Duplicate records were removed through a two-stage procedure. First, automated matching based on Digital Object Identifiers (DOIs) and exact title correspondence was performed using Microsoft Excel. Second, manual verification was conducted to resolve inconsistencies associated with missing DOIs, variations in author names, or minor title differences.

Metadata quality was subsequently verified, including publication titles, abstracts, author names, institutional affiliations, publication years, journal titles, keywords, and research categories. Standardization procedures were applied to harmonize author and institutional names, improving consistency in subsequent bibliometric analyses.

The numbers of records retrieved from the two databases, the number of duplicates removed, and the number of unique records retained for screening were documented separately. Duplicate identification was based on DOI matching and exact-title matching, followed by manual verification where discrepancies occurred. All cleaning and deduplication decisions were recorded in Microsoft Excel to maintain an auditable record of the selection process. The final counts were transferred to the PRISMA 2020 flow diagram (Figure 1).

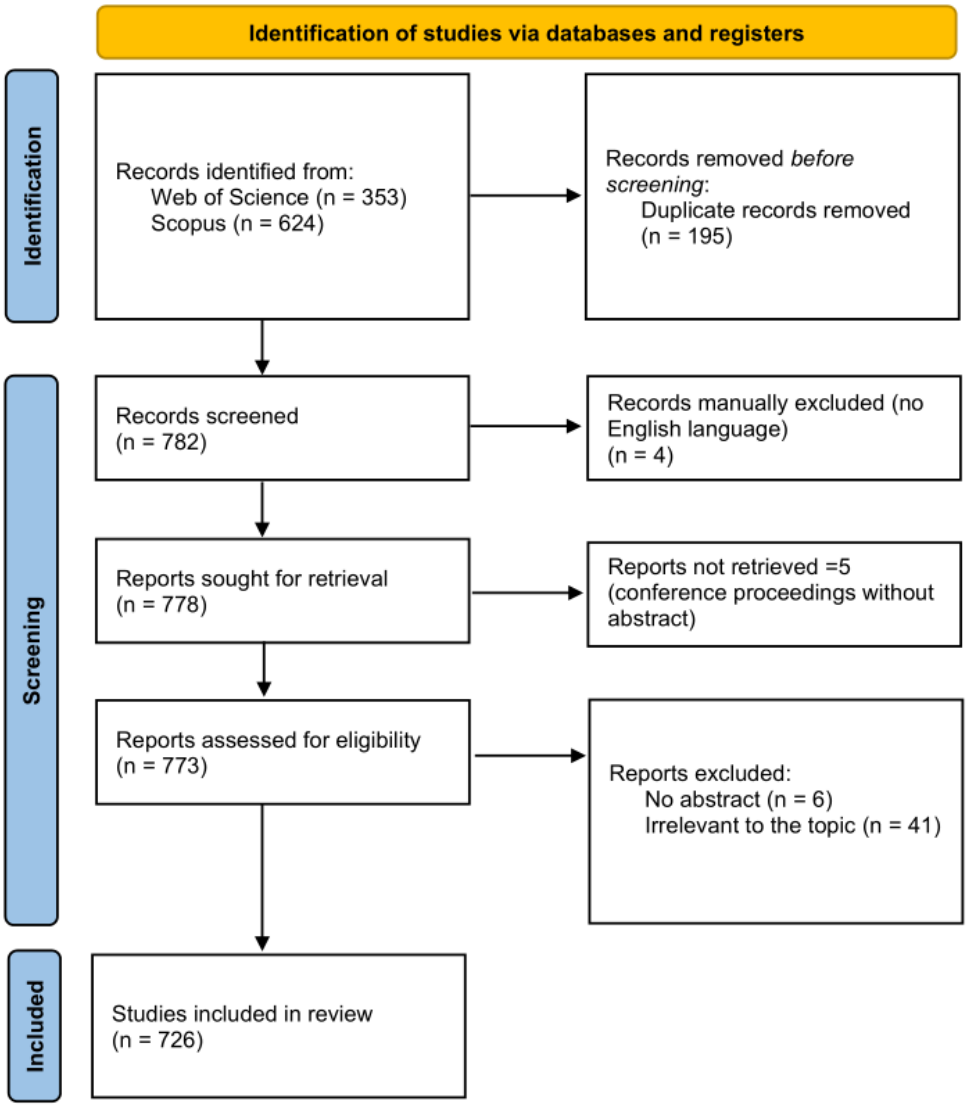


Figure 1. Selection process of the eligible reports based on the PRISMA 2020 flow diagram.

2.1.5. Selection Criteria and Screening Procedure

Study selection followed two stages: title and abstract screening, followed by full-text assessment. Two reviewers independently screened titles and abstracts against the predefined eligibility criteria. Records considered potentially relevant by either reviewer were advanced to full-text assessment. Full texts were assessed independently by both reviewers. Disagreements were resolved through discussion and, when necessary, consultation with a third reviewer.

Inclusion criteria:

- Peer-reviewed research articles and review articles, together with proceedings papers and book chapters meeting the publication-type requirements specified in Section 2.1.3;
- Publications written in English;
- Studies investigating copper pollution, contamination, accumulation, or distribution in agricultural soils;
- Research addressing copper sources, environmental behavior, soil chemistry, bioavailability, toxicity, crop uptake, ecological risks, or remediation strategies;
- Publications providing sufficient information to establish their relevance and support the intended synthesis.

Exclusion criteria:

- Non-peer-reviewed publications and publication types outside the eligibility criteria;
- Studies unrelated to agricultural soils or terrestrial farming systems;
- Studies focused exclusively on copper in industrial, aquatic, or other non-agricultural environments;
- Studies in which copper was mentioned only incidentally and was not a substantive research focus;
- Records for which the full text could not be retrieved;
- Publications lacking sufficient information to determine eligibility or support meaningful interpretation.

Screening decisions and reasons for exclusion were documented in Microsoft Excel. Inter-reviewer agreement was assessed using percentage agreement.

At the full-text stage, exclusion reasons were recorded using the following categories: (A) out of scope; (B) non-peer-reviewed or ineligible publication type; (C) insufficient relevant information; (D) full text unavailable; and (E) inadequate methodological information. Each excluded record was assigned a documented primary reason for exclusion, and the corresponding counts were used in the PRISMA 2020 flow diagram.

2.1.6. Final Dataset and Bibliometric Variables

Data processing and bibliographic record management were performed using Microsoft Excel, the Web of Science Core Collection, Scopus, and Geochart [38–41]. Records exported from Scopus and the Web of Science Core Collection were consolidated in Microsoft Excel. Duplicate records were identified and removed using DOI matching, exact-title matching, and manual verification, as described in Section 2.1.4. Bibliographic metadata were checked and standardized in Excel to improve consistency in author names, institutional affiliations, publication titles, and keywords. The consolidated records were used for bibliometric visualization in VOSviewer (version 1.6.20) [42]. No dedicated bibliometric data-merging package, such as Bibliometrix, was used.

Following screening and eligibility assessment, the final corpus comprised 726 publications addressing copper pollution in agricultural soils. This corpus served as the basis for the bibliometric analyses. The qualitative content analysis focused on a subset of 115 representative articles selected from the final corpus according to their relevance to the principal research themes. The number of records included in individual bibliometric analyses depended on the availability and completeness of the required metadata. Where a smaller analytical subset was used, its size and the reason for the reduction are reported in the relevant Results subsection and figure caption.

Bibliometric indicators included publication type, research discipline, annual publication trends, geographic distribution, authorship patterns, institutional affiliations, journal sources, publishing outlets, and keyword occurrence. Data processing and statistical analyses were conducted using the Web of Science Core Collection, Scopus, Microsoft Excel, and Geochart. Co-authorship networks, co-citation structures, and keyword co-occurrence patterns were visualized using VOSviewer (version 1.6.20).

For the bibliometric analysis, counting procedures were applied consistently across the analyzed records. Annual publication output was calculated by assigning each publication to its year of publication, with each record counted once per year. Journal productivity was assessed by counting the number of publications attributed to each journal. Research-area frequencies were determined from the subject categories assigned to the retrieved records; because a publication could be indexed in more than one category, the sum of category frequencies may exceed the total number of publications. Country contributions were determined from the country affiliations associated with each publication. For

publications involving authors affiliated with institutions in multiple countries, each represented country was counted, meaning that country-level totals may exceed the number of unique publications.

Network analyses were conducted using VOSviewer (version 1.6.20), with the software's default settings retained for the analyses performed. No dedicated bibliometric merging package was used; records from Scopus and the Web of Science Core Collection were consolidated and deduplicated in Microsoft Excel before analysis. The keyword co-occurrence analysis was based on author keywords, with terms used in the search strategy excluded from the frequency analysis. No manually prepared thesaurus file was used to merge synonyms. Consequently, equivalent terms or spelling variants may have remained separate in the keyword network. These procedures distinguish publication-level counts from country, subject-category, and keyword frequencies, which may involve multiple assignments per publication.

Figures from Section 3.1 were generated using a subset of 353 articles indexed in the Web of Science (WoS) database, as these analyses relied on WoS-specific metadata, whereas the complete merged dataset comprised 726 records retrieved from WoS and Scopus.

2.1.7. Quality Assessment and Risk of Bias

The methodological quality of the included studies was considered during full-text assessment and qualitative synthesis. Attention was given to the clarity of research objectives, the appropriateness of study designs, the description of sampling and analytical procedures, the suitability of the methods used to determine copper concentrations or assess related environmental effects, and the adequacy of the evidence supporting the reported conclusions. Particular consideration was given to whether the methods and results were described sufficiently to evaluate the relevance and interpretability of the findings. No standardized risk-of-bias assessment instrument was applied; therefore, the methodological considerations described above should not be interpreted as a formal risk-of-bias assessment. Potential methodological limitations were considered when interpreting the evidence and synthesizing the findings, and the conclusions were framed in accordance with the information available in the included publications.

2.2. Qualitative Content Analysis

In parallel with the bibliometric assessment, a qualitative content analysis was conducted to identify dominant research themes, conceptual approaches, methodological trends, and knowledge gaps concerning copper pollution in agricultural soils. The qualitative synthesis was based on the representative articles form the database.

The publications were examined and classified into seven thematic clusters: (1) research trends and investigated approaches for copper-contaminated agricultural soils; (2) global occurrence of copper contamination in agricultural soils and country case studies; (3) analytical methods for determining copper pollution in agricultural soils; (4) impacts of copper contamination on agricultural soil properties, microbial communities, and nutrient cycling; (5) effects of copper contamination on crop growth, metal uptake, and plant responses; (6) characteristics of copper and multi-metal contamination in agricultural soils; and (7) approaches for remediating copper-polluted agricultural soils (Figure 2).

The thematic framework was developed inductively from the selected publications. Two reviewers independently coded the articles. Multiple thematic assignments were permitted when a publication addressed more than one substantive topic. Disagreements were resolved through discussion and consensus, and coding decisions were documented in Microsoft Excel.

The seven thematic clusters provided the organizational framework for the corresponding Results and Discussion subsections. They were used to synthesize the scope, methods, principal findings, and research gaps in the literature, rather than to imply that each publication addressed only one theme.

The bibliometric analysis was conducted using the entire final corpus of 726 eligible articles, whereas the qualitative literature review focused on 115 representative articles selected from this corpus based on their relevance to the main research themes. The table representing themMain research aspects investigated in scientific studies presents 25 studies selected from these 115 articles to illustrate the main research aspects of copper pollution in agricultural soils, including its sources, environmental impacts, and remediation approaches.

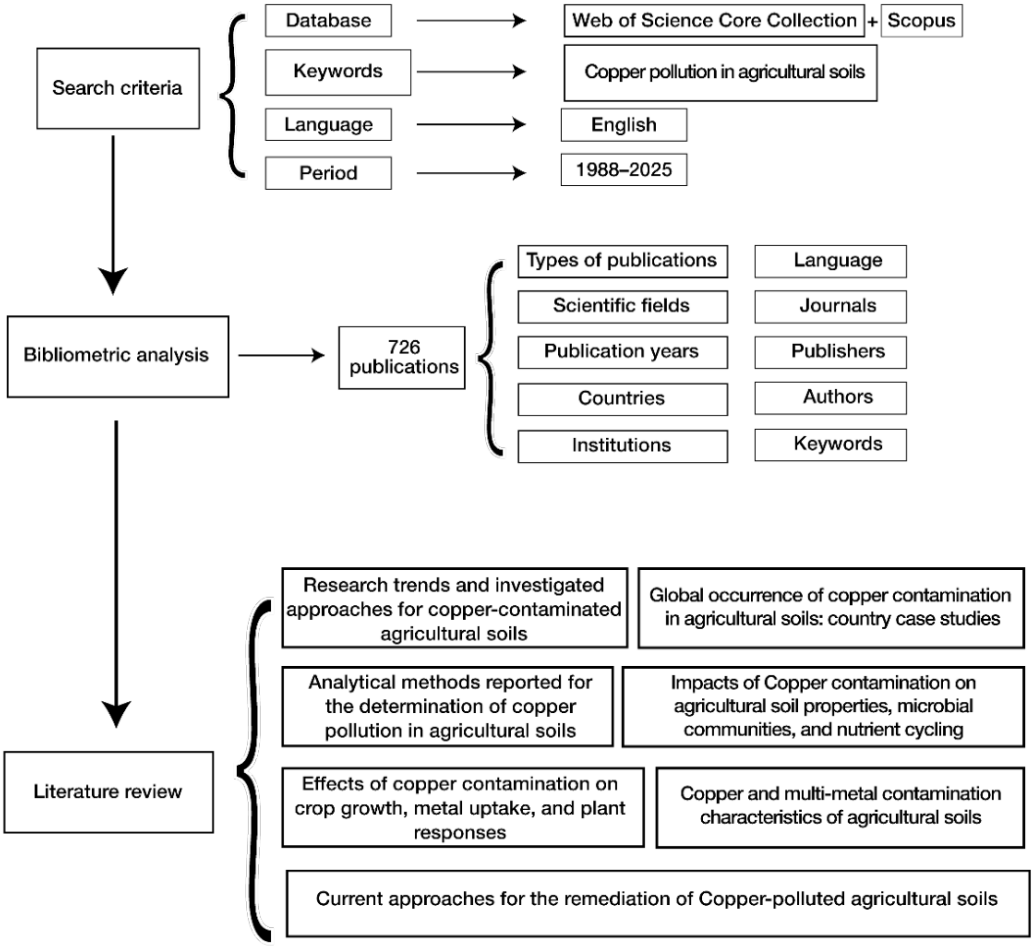


Figure 2. Schematic presentation of the workflow used in our research.

3. Results

3.1. A Bibliometric Review

The temporal distribution of published articles indicates an increase in research output across the periods 2010–2020 and 2020–2025 (Figure 3). The highest annual publication output, comprising 67 articles, was recorded in both 2023 and 2024. These results indicate sustained research activity in recent years. However, the identification of distinct growth phases requires a quantitative comparison of publication counts or growth rates across predefined periods. Accordingly, the periods described here are used to summarize the observed temporal pattern rather than to imply statistically distinct phases of development.

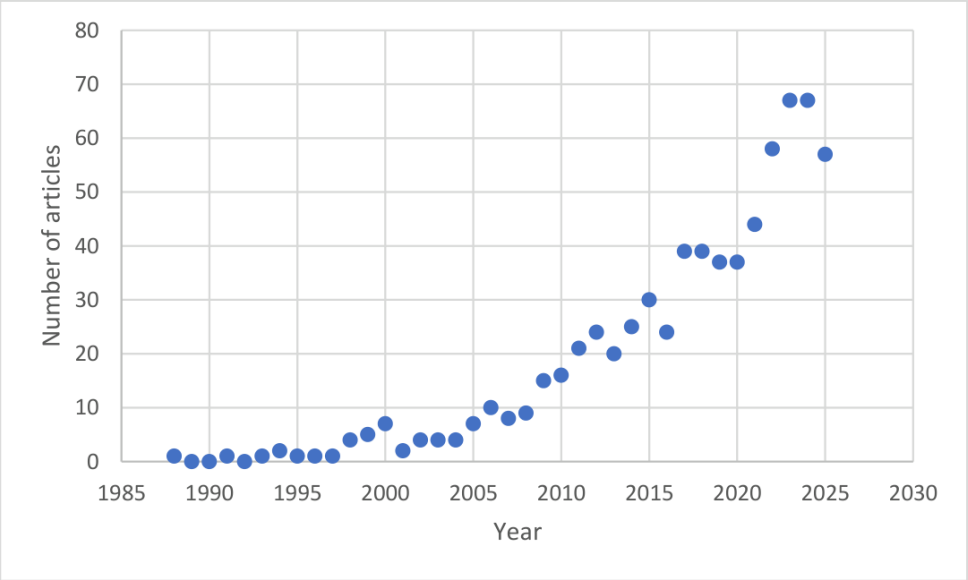


Figure 3. Representation of the number of publications by year on agricultural soils polluted with copper.

The bibliometric analysis revealed that environmental and agricultural sciences were the principal research areas, reflecting the multidisciplinary nature of research on Cu pollution in agricultural soils (Figure 4). Among the 726 publications, journal articles accounted for 661 records (91%), followed by review articles (28; 4%), proceedings papers (26; 4%), and book chapters (11; 1%). These findings indicate that journal articles constitute the main publication type in the analyzed dataset.

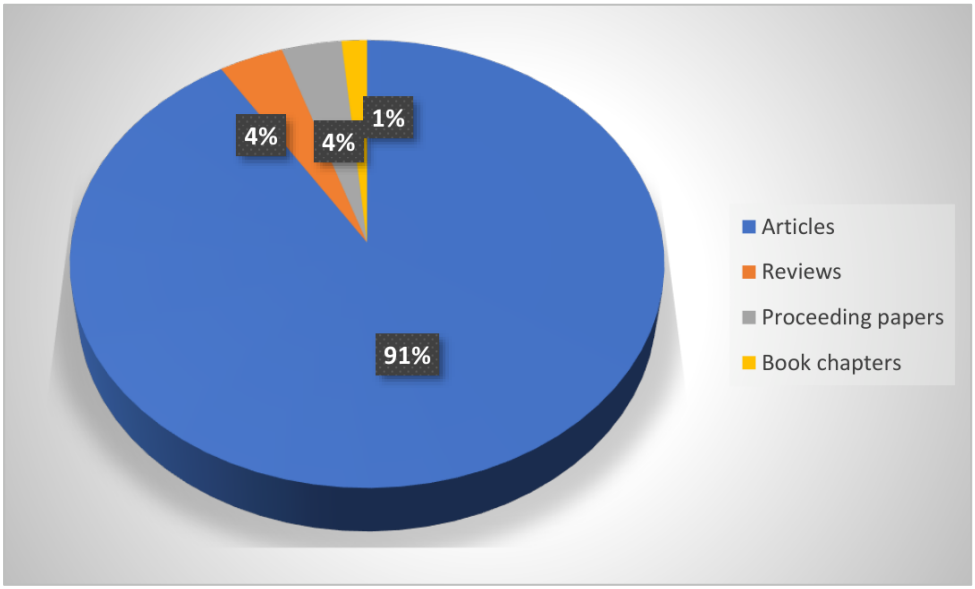


Figure 4. Overview of the principal publication types on agricultural soils polluted with copper.

Research-area frequencies were based on the subject categories assigned to the retrieved records. Environmental Sciences and Ecology was the leading field (192 records), followed by Agriculture (65), Engineering (39), Water Resources (35), and Science Technology Other Topics (34). Because publications may be assigned to multiple subject categories, these frequencies represent category assignments rather than mutually exclusive groups of publications. The distribution highlights the importance of soil quality, environmental

fate, remediation strategies, and impacts on agricultural ecosystems. The presence of Plant Sciences, Chemistry, Toxicology, Geochemistry, and Microbiology further emphasizes the importance of understanding copper behavior, bioavailability, plant uptake, and biological responses (Figure 5).

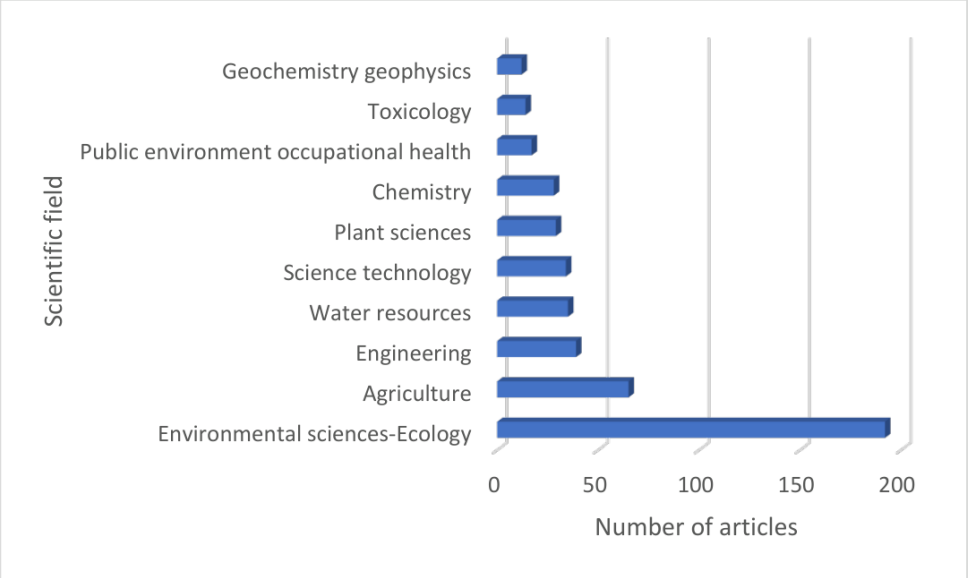


Figure 5. Overview of the principal scientific fields on agricultural soils polluted with copper.

The geographical distribution indicates that research on copper pollution in agricultural soils has attracted contributions from many regions worldwide China was the most productive country (103 publications), followed by India (21), Iran (20), the USA (19), Italy (16), Pakistan (16), and Spain (16). Country contributions were determined from the affiliation information associated with the retrieved publications. Because a publication may include authors affiliated with institutions in multiple countries, country-level frequencies are not mutually exclusive. The high publication output from China and other Asian countries may be associated with research priorities related to agricultural production, industrial activity, and soil contamination. However, publication counts alone do not establish the extent of soil contamination or the relative severity of environmental problems in these countries. Similarly, the involvement of European countries indicates substantial research activity but does not, by itself, demonstrate the effectiveness of their soil-monitoring or environmental-protection policies.

The countries, represented by the authors' institutional affiliations on this topic, can be organized into three clusters, each comprising at least four countries. These clusters are as follows: Cluster 1 includes Brazil, Chile, France, Italy, Russia, Spain and USA; Cluster 2 consists of Australia, England, Iran and Turkey; Cluster 3 consists of Egypt, Germany, Greece and Mexico; Cluster 4 includes India, Pakistan, Saudi Arabia and South Korea; Cluster 5 includes Belgium, China, Poland and Taiwan (Figure 6). Since each cluster includes countries from different continents, no clear geographical pattern of grouping could be identified; it seems that connections between authors are the main factor driving these associations.

Among the 197 journals that published articles on this topic, the most representative were *Environmental Science* and *Pollution Research* (16 articles), *Science of the Total Environment* (13 articles), and *Environmental Pollution* (11 articles) (Table 1 and Figure 7). Journal productivity was determined by counting the publications attributed to each journal, with each publication assigned to its corresponding source journal.

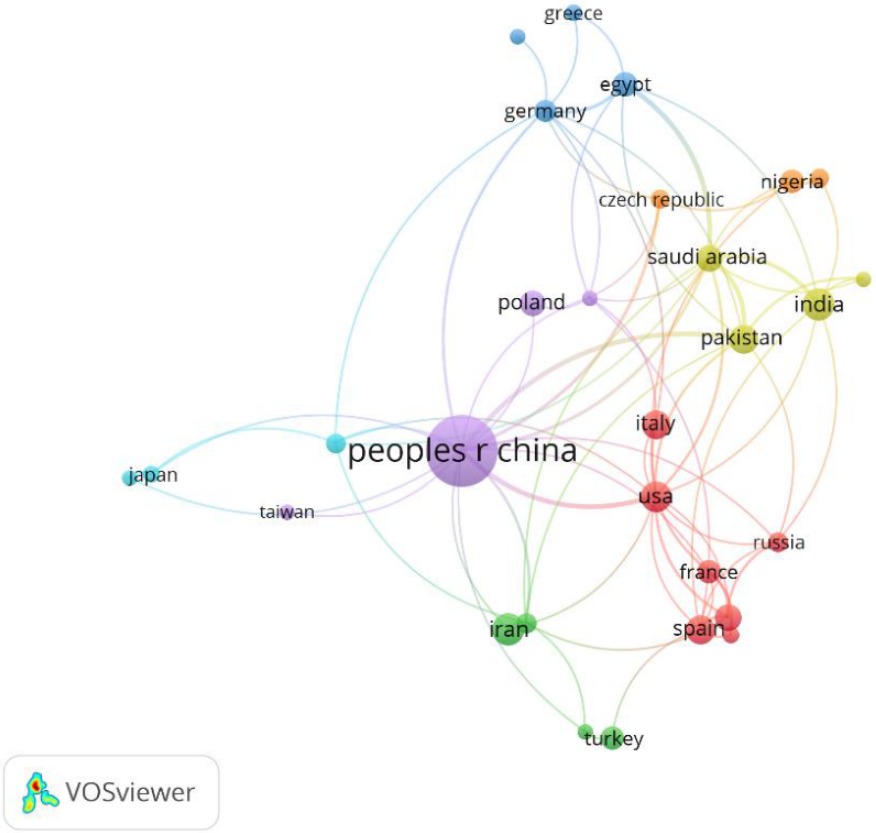


Figure 6. Clusters of countries with authors of articles on agricultural soils polluted with copper.

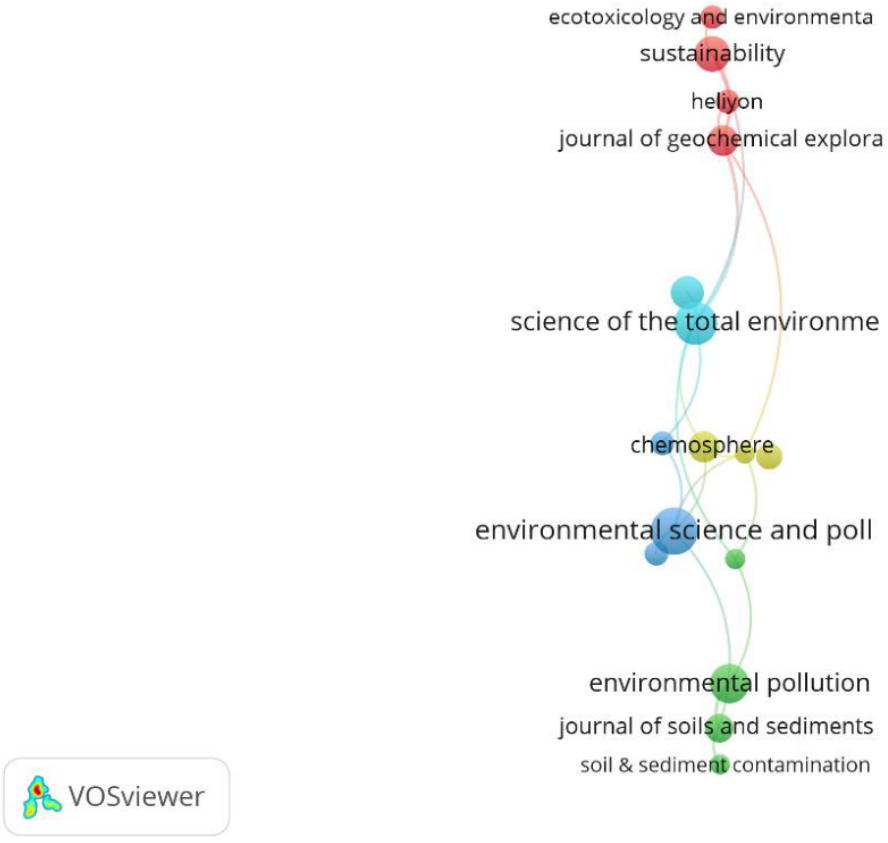


Figure 7. The leading journals that have published articles on agricultural soils polluted with copper.

Table 1. The leading journals that have published articles on agricultural soils polluted with copper.

Crt. No.	Journal	Documents	Citations	Total Link Strength
1	*Science of the Total Environment*	13	1348	7
2	*Journal of Geochemical Exploration*	7	550	6
3	*Environmental Science and Pollution Research*	16	423	5
4	*Geoderma*	3	228	5
5	*Journal of Soils and Sediments*	6	214	4
6	*Sustainability*	9	102	4
7	*Agriculture*	3	7	4
8	*Chemosphere*	7	666	4
9	*Environmental Pollution*	11	475	3
10	*Journal of Environmental Management*	4	207	2
11	*Environmental Geochemistry and Health*	8	211	1
12	*Environmental Monitoring and Assessment*	6	137	1

In terms of institutional affiliation, the most representative institutions for authors publishing on this topic were the Chinese Academy of Sciences (26 articles), Consiglio Nazionale delle Ricerche (9 articles) and Huazhong Agricultural University (with 8 articles). Like in other topics, China is among the leading countries. The leading publishers in this research domain included Elsevier (94 articles), Springer Nature (68 articles), MDPI (35 articles) and Taylor & Francis (25 articles).

The most frequently occurring author keywords, excluding the terms used in the search strategy (copper, agricultural soils, and related search terms), were heavy metals, cadmium, accumulation, and pollution. Table 2 presents the 14 most frequent keywords, ranked by their number of occurrences. Total link strength is reported separately to indicate the strength of keyword co-occurrence relationships.

Table 2. The 14 most frequent author keywords in studies on copper pollution in agricultural soils, ranked by number of occurrences.

Crt. No.	Keyword	Occurrences	Total Link Strength
1	Heavy metals	198	664
2	cadmium	75	326
3	pollution	59	229
4	accumulation	56	271
5	contamination	52	215
6	lead	46	226
7	zinc	45	200
8	soil	42	140
9	bioavailability	34	165
10	plants	34	152
11	toxicity	31	119
12	phytoremediation	29	120
13	Trace elements	28	131
14	Contaminated soils	24	113

The keyword co-occurrence network revealed four main clusters (Figure 8). Cluster 1 (red) comprised terms related to soil pollution and contamination, including pollution, contamination, soil, water, ecological risk, spatial distribution, and source apportionment. Cluster 2 (green) mainly included terms associated with copper and other heavy metals, such as copper, heavy metals, accumulation, lead, zinc, toxicity, and phytoremediation. Cluster 3 (blue) contained keywords referring to specific metals and their remediation,

including cadmium (cd), lead (pb), copper (cu), and zinc (zn), together with removal and remediation-related terms. Cluster 4 (yellow) focused on soil contamination and metal behaviors, including contaminated soils, polluted soils, adsorption, and bioavailability. These clusters illustrate the interconnected research themes concerning the occurrence and assessment of metal pollution in soils, the behaviors of metals in the soil environment, and approaches to remediation. The clusters represent groups of terms linked by their co-occurrence in the analyzed records and summarize the principal thematic associations identified in the keyword network.

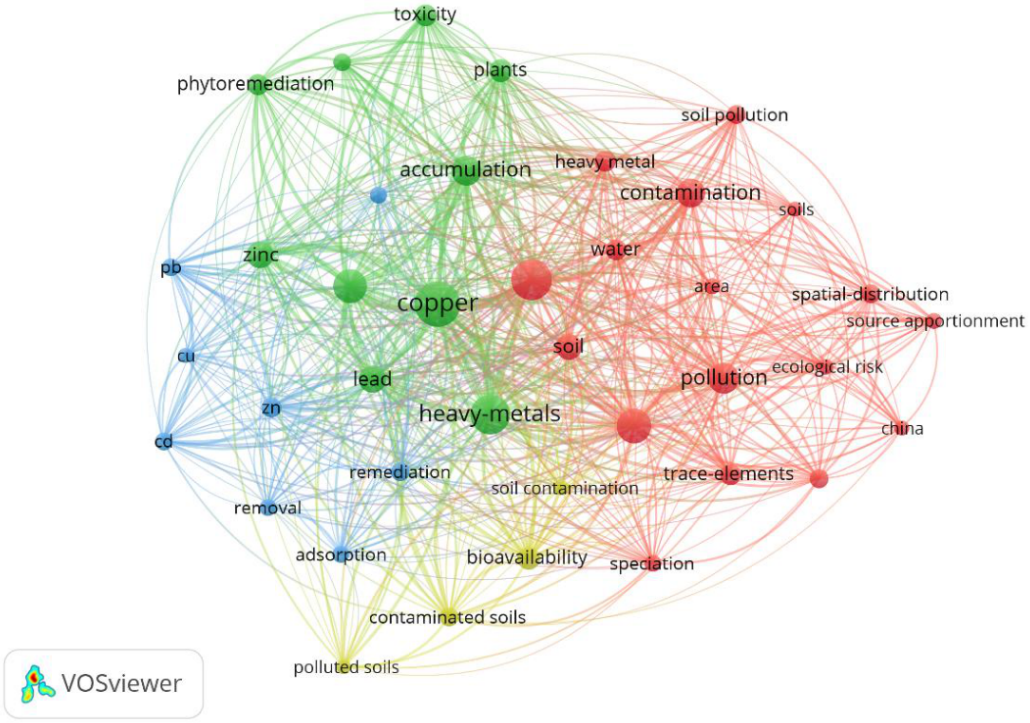


Figure 8. Keywords used by authors in relation to agricultural soils polluted with copper.

3.2. Literature Review

3.2.1. Research Trends and Approaches Investigated for Copper-Contaminated Agricultural Soils

To identify the main research directions and approaches used to investigate Cu pollution in agricultural soils, selected publications were classified according to their research focus, geographical setting, and principal contributions (Table 3). The studies in Table 3 were selected from the eligible publications identified through the systematic search and screening process. They illustrate key aspects of Cu contamination in agricultural soils, including its sources, environmental effects, analytical methods, and remediation approaches.

The selected studies indicate that research on copper contamination in agricultural soils covers several major directions, including contamination assessment, environmental impacts, plant responses, monitoring techniques, and remediation approaches. The reviewed studies demonstrate that copper pollution has been investigated in different geographical regions and under various contamination scenarios, including industrially influenced areas, agricultural fields, vineyard soils, and mining-affected environments.

Table 3. Main research aspects investigated in scientific studies on copper-contaminated agricultural soils.

Cur. No.	Studied Aspect	Location	Cited by
1	Analysis of copper tolerant rhizobacteria from the industrial belt of Gujarat, western India for plant growth promotion in metal polluted agriculture soils	India	Sharaff et al., 2017 [43]
2	Assessment of Cu in Wheat (*Triticum aestivum* L.) and Arable Land in the Vicinity of Bor (Serbia): Implications for Food Safety and Human Health	Serbia	Simonovic et al., 2026 [44]
3	Bioavailability and bioaccumulation characterization of essential and heavy metals contents in *R. acetosa*, *S. oleracea* and *U. dioica* from copper polluted and referent areas	North Macedonia	Balabanova et al., 2015 [45]
4	Characterization of copper-resistant bacteria and bacterial communities from copper-polluted agricultural soils	Chile	Altimira et al., 2012 [46]
5	Contribution of inoculation with arbuscular mycorrhizal fungi to the bioremediation of a copper contaminated soil using *Oenothera picensis*	Chile	Cornejo et al., 2017 [47]
6	Contributions on enhancing the copper uptake by using natural chelators, with applications in soil phytoremediation	Romania	Dumbrava et al., 2015 [48]
7	Copper in Surface Layer of Vineyard Soils on Island Hvar	Croatia	Runjic and Custovic, 2017 [49]
8	Copper in the surface layer of the farmland soils in Poland	Poland	Terelak et al., 2003 [50]
9	Copper stress in rice: Perception, signaling, bioremediation and future prospects	Bangladesh	Rob et al., 2024 [51]
10	Earthworm colonisation of abandoned arable soil polluted by copper	Denmark	Holstrup and Hornum, 2012 [52]
11	Efficiency of Soil Amendments for Copper Removal and *Brassica Juncea (L.)* Growth in Wastewater Irrigated Agricultural Soil	Pakistan	Bashir et al., 2022 [53]
12	Electrokinetic remediation of copper-contaminated agricultural soils	Spain	Navas-Higuero et al., 2025 [54]
13	Field-based evidence for copper contamination induced changes of antibiotic resistance in agricultural soils	China	Hu et al., 2016 [55]
14	Hyperspectral Inversion of Soil Cu Content in Agricultural Land Based on Continuous Wavelet Transform and Stacking Ensemble Learning	China	Yang et al., 2024 [56]
15	Hyperspectral Visible and Near-Infrared Determination of Copper Concentration in Agricultural Polluted Soils	Italy	Antonucci et al., 2012 [57]
16	Immobilization of soil copper using organic and inorganic amendments	Egypt	Shaheen et al., 2015 [58]
17	Impact of dual inoculation with *Rhizobium* and PGPR on growth and antioxidant status of *Vicia faba* L. under copper stress	Tunisia	Fatnassi et al., 2015 [59]

Table 3. *Cont.*

Cur. No.	Studied Aspect	Location	Cited by
18	In vitro and in vivo copper-treated *Myrtus communis* L.: terpene profiles and evidence for potential cultivation on metal-contaminated soils	Italy	Capuana et al., 2023 [60]
19	Nutrients Can Enhance Phytoremediation of Copper-Polluted Soil by Indian Mustard	China	Wu et al., 2004 [61]
20	Pear twig biochar combined with nitrogen fertilizer regulates morpho-physiological growth, copper uptake and tuber quality of potato (*Solanum tuberosum* L.) grown in polluted soil	China	Wang et al., 2024 [62]
21	Remediation of Cu Contaminated Agricultural Soils near Oilfields by Biochar Combined with Sodium Humate-Wood Vinegar	China	Wang et al., 2023 [63]
22	Selective copper immobilization in contaminated soils using cysteine-modified chitosan	China	Li et al., 2025 [64]
23	Study on remediation of alkaline soil polluted by copper and cadmium by MICP combined with modified oyster shell powder	China	Chen et al., 2025 [65]
24	the potential of different jute varieties for phytoremediation of copper-contaminated soil	China	Saleem et al., 2020 [66]

A considerable number of studies have focused on the presence and distribution of copper in agricultural soils. Investigations performed in vineyard soils and farmland areas have assessed Cu accumulation in surface soil layers, where long-term agricultural practices may contribute to increased metal concentrations [49,50]. Studies conducted near mining areas have evaluated copper levels in agricultural soils and crops, with emphasis on possible implications for food safety and human exposure [44].

The effects of copper contamination on soil biological components have also been widely studied. Research has examined microbial adaptation, resistance mechanisms, and community changes in copper-polluted soils. The characterization of copper-resistant bacteria and microbial communities has been reported in contaminated agricultural soils [46]. In addition, the influence of Cu contamination on antibiotic resistance patterns in agricultural environments has been investigated, indicating possible interactions between metal pollution and microbial resistance development [55]. Soil fauna responses have also been considered, including earthworm colonization and activity in copper-affected soils [52].

Plant-related studies represent another important research area. Several articles have evaluated Cu uptake, accumulation, and tolerance mechanisms in different plant species. Metal accumulation patterns were studied in edible and wild plants collected from copper-polluted and reference areas [45]. Research has also investigated crop responses to Cu stress, including physiological effects and possible remediation strategies in plants such as rice [51]. The phytoremediation potential of different plant species, including jute varieties, has been examined for copper-contaminated soils [56].

The role of microorganisms associated with plants has been investigated as a method for improving plant growth and reducing copper stress. Copper-tolerant rhizobacteria have been studied for their ability to support plant development in metal-contaminated soils [43]. The contribution of arbuscular mycorrhizal fungi to copper remediation using *Oenothera picensis* has also been evaluated [47]. Other studies have examined combined inoculation approaches involving rhizobia and plant growth-promoting bacteria under copper stress conditions [59].

Remediation methods constitute a large proportion of the reviewed research. Phytoremediation approaches have been investigated through the use of plants, nutrient additions, and chelating agents to increase Cu removal or tolerance. The enhancement of copper uptake using natural chelators has been studied as a possible remediation strategy [48], while nutrient management has been evaluated to improve phytoremediation efficiency [61].

Soil amendment technologies have also received considerable attention. Different organic and inorganic materials have been investigated for reducing copper mobility and improving soil quality. Studies have evaluated copper immobilization using amendments [58], biochar-based treatments [62,63], and amendment combinations for wastewater-irrigated agricultural soils [53]. More advanced techniques, including electrokinetic remediation, have been explored for copper removal from contaminated agricultural soils [54].

Recent studies have focused on the development of specialized materials for copper extraction or stabilization. Modified chitosan materials have been tested for selective Cu immobilization in contaminated soils [64]. Combined remediation approaches, such as microbial-induced calcite precipitation with modified oyster shell powder, have also been proposed [65].

Monitoring and detection methods represent an emerging research direction. Traditional chemical analysis has been complemented by rapid and non-destructive techniques, including hyperspectral approaches for estimating soil copper concentrations. Visible and near-infrared spectroscopy methods have been applied for Cu determination in polluted agricultural soils [57], and more recent approaches have used advanced modelling techniques to improve Cu prediction accuracy [56].

Other studies have examined copper effects in specific plant systems and contaminated environments. The response of *Myrtus communis* exposed to copper has been investigated, including its potential use in metal-contaminated areas [60]. Additional research has addressed complex contamination situations involving multiple metals and combined remediation methods [65].

3.2.2. Global Occurrence of Copper Contamination in Agricultural Soils: Country Case Studies

Europe

Germany

Copper contamination in agricultural soils in Germany has been associated with both industrial emissions and long-term atmospheric deposition. In Hamburg, heavy metals including As, Pb, Cu, Zn, Cd, Cr and Ni were investigated in surface soils and soil profiles. The study showed that Cu and other metals were accumulated mainly due to historical industrial activities, particularly emissions from a large copper-processing plant located in the southeast of the city. The estimated enrichment caused by airborne industrial deposition reached approximately 2900 tonnes of Cu over an area of 190 km^2. Soil monitoring also indicated that Cu and Zn behaved differently from other metals, with no clear decrease trends despite changes in atmospheric inputs, suggesting their persistence in soils [67].

Croatia

In Croatia, copper contamination has been linked mainly to agricultural practices, especially the historical use of copper-based fungicides in vineyards. A study conducted in Primošten, Middle Dalmatia, compared Terra rossa soils under former vineyards converted to olive groves with soils under natural vegetation. The results showed significantly higher Cu concentrations in olive groves (199.3 mg kg^{-1}) compared with natural vegetation soils (51.8 mg kg^{-1}). The enrichment factor indicated moderate to significant Cu accumulation

in cultivated soils, demonstrating the long-term effect of agricultural management practices on Cu accumulation [68].

Italy

In Italy, copper pollution has been studied in agricultural systems affected by intensive vineyard management. A study investigating an old vineyard converted into a protected area found that total Cu reached approximately 1000 mg kg^{-1} in vineyard tree rows, whereas other treatments contained less than 80 mg kg^{-1}. The high Cu concentration resulted from repeated applications of copper-containing fungicides. However, ecological restoration improved soil biochemical properties and microbial functions, indicating that conservation practices may reduce the negative effects of Cu contamination. Changes in bacterial community composition showed adaptation to Cu stress, while fungal communities were less affected [69].

Greece

Copper contamination in Greek soils has been assessed in agricultural, industrial and forest areas. Research conducted in the Almyros region evaluated total and available concentrations of Cd, Cr, Cu, Pb, Zn and Ni. Agricultural soils showed relatively lower contamination compared with industrial sites, but Cu presented the highest enrichment factor among the studied metals, indicating a significant contribution of anthropogenic activities to Cu accumulation [70].

Cyprus

In Cyprus, agricultural soil contamination has been associated with mining activities. At the abandoned Limni mine, tailings were identified as a source of Cu, Zn, Pb, and sulfur contamination in surrounding areas. Copper concentrations exceeded the applicable permissible levels in tailings and nearby soils, while enrichment-factor and geo-accumulation-index values indicated severe contamination. The study also reported elevated concentrations of potentially toxic elements in crops, including figs, peanuts, lemons, and barley. These findings indicate a potential food-safety concern; however, the detection of metals in crops alone does not establish a human-health risk. Such a conclusion requires comparison with relevant food standards and, where appropriate, an exposure assessment. Phytostabilisation using native plant species was proposed as a possible management strategy [71].

Denmark

Copper contamination in Denmark has been investigated through its effects on soil organisms. At the Hygum contaminated site, copper concentrations influenced earthworm distribution. In 1994, earthworm species were restricted to areas with Cu concentrations below 200 mg kg^{-1}. After 16 years without agricultural activity, more species were observed, including in areas where soil Cu exceeded 1000 mg kg^{-1}, suggesting gradual ecological adaptation and recovery processes after reduced disturbance [52].

Romania

In Romania, agricultural soil contamination by Cu and other heavy metals has been investigated with emphasis on remediation methods. A study evaluated phytoremediation using *Brassica juncea* combined with EDTA in soils contaminated with Zn, Cu and Pb. The combined treatment improved metal removal efficiency, achieving reductions of 27.5% for Cu, 51.5% for Zn and 36.3% for Pb. The results indicated that combined phytoextraction and chelation approaches may provide effective strategies for restoring contaminated agricultural soils [72].

Poland

Copper concentrations in Polish agricultural soils have generally remained close to natural levels, although industrialized areas show greater accumulation. A national-scale study reported Cu concentrations ranging from 0.2 to 725 mg kg^{-1}, with approximately 97% of agricultural soils classified as unpolluted. More strongly contaminated soils represented only a small proportion of farmland, mainly located in industrial regions where anthropogenic emissions increased Cu levels [50].

Turkey

In Turkey, copper contamination has been associated with industrial activities near agricultural areas. In Tekkeköy, Samsun, soils around copper smelting and fertilizer plants showed high concentrations of Cu, Zn, Pb, Fe and Mn. Pollution was concentrated mainly in the surface layer, decreasing sharply below 20 cm depth. Crops such as tobacco, maize and cabbage accumulated Cu and other metals, demonstrating the transfer of industrial contaminants into agricultural systems [73].

Georgia

Copper accumulation in Georgian agricultural soils has been linked to irrigation practices and intensive farming. Studies in the Kvemo Kartli region found that available Cu and Zn were mainly associated with irrigation water and fungicide use. Simulation analyses indicated that intensive application of copper-based fungicides, particularly in vineyards, contributed more significantly to Cu accumulation than irrigation water. Soil contamination indices confirmed higher Cu enrichment in vineyard soils compared with other agricultural land uses [74].

Asia

China

Copper contamination in agricultural soils in China has been reported particularly in areas affected by mining and metallurgical industries. Around the Daye Copper Smelter in Hubei Province, agricultural soils contained elevated concentrations of Cu, Cd, Pb, and As. The mean Cu concentration in contaminated soils was 195.26 mg kg^{-1}, compared with 32.84 mg kg^{-1} in reference soils. Contamination was also detected in vegetables, rice, and fish, indicating the presence of these elements in food-related environmental pathways. The cited study included a health-risk assessment that identified agricultural-product consumption as an exposure pathway and reported greater vulnerability among children living near the smelter [75]. These findings should be interpreted within the exposure assumptions and risk-assessment methods used in that study and should not be generalized to other agricultural regions without supporting evidence.

Contamination was also detected in vegetables, rice, and fish, indicating that metals may be transferred from contaminated environmental media into food products. The reported health-risk assessment identified agricultural-product consumption as an important potential exposure pathway, particularly for children living near the smelter [76]. These findings support concern about exposure in the investigated area; however, the contribution of Cu to the estimated risk should be distinguished from that of co-occurring metals, and the findings should not be generalized to other agricultural soils without considering local contamination levels, crop uptake, dietary exposure, and the risk-assessment assumptions.

A global assessment of soils near copper mining sites showed that Cu contamination is a widespread issue. The study included 102 copper mining locations worldwide and found that agricultural soils near mining areas were more affected by heavy metals than non-agricultural soils. Copper, together with Cd and As, represented one of the main

contributors to ecological risk. The results highlighted the need to prioritize Cu control strategies in mining-affected agricultural regions [76].

India

In India, copper contamination of agricultural soils has been reported in areas influenced by mining activities. In the Singhbhum shear zone, agricultural soils near copper mining and processing areas showed elevated concentrations of Cu and other metals. Pollution indices including enrichment factor, geo-accumulation index and contamination factor indicated very high Cu contamination compared with natural background levels. The study identified anthropogenic activities related to mining as the main source of metal accumulation and recommended continuous monitoring of agricultural soils [77].

Iran

Copper contamination in Iran has been studied in agricultural soils surrounding mining areas. Near the Zarshouran gold mine, soil samples showed increased concentrations of several heavy metals, including Cu. The average Cu concentration reached 65.06 mg kg^{-1}, with enrichment analysis indicating considerable Cu accumulation due to mining activities. Although Cu was mainly associated with stable soil fractions, its presence in more mobile fractions indicated potential environmental risks under changing soil conditions [78].

Iraq

Urban and agricultural soils in Iraq have shown evidence of heavy metal contamination caused by industrial activities. In Baghdad, soil analyses demonstrated increased concentrations of Cu, Cd, Cr, Ni, Pb and Zn, particularly in industrial areas. The highest pollution indices were recorded in industrial soils, suggesting strong anthropogenic influence. Copper was among the metals contributing to multi-element contamination and environmental degradation [79].

Africa

Egypt

Copper behavior in agricultural soils of Egypt has been investigated in newly reclaimed agricultural areas. In the 10th of Ramadan region, total Cu concentrations ranged from 4.88 to 19.19 mg kg^{-1}, while extractable Cu ranged from 1.56 to 4.51 mg kg^{-1}. Sequential extraction showed that residual Cu was the dominant fraction, representing the least mobile form, followed by Cu associated with Fe-Mn oxides. The study indicated that soil properties, including mineral composition, organic matter and pH, strongly influenced Cu availability and mobility [80].

Algeria

In Algeria, Cu contamination in agricultural soils has been linked mainly to urban and agricultural activities. A large-scale investigation around Annaba analyzed Cd, Cr, Cu, Pb and Zn in surface soils. Copper was the only element showing significant spatial autocorrelation, and spatial analysis identified agricultural activities as the main source of Cu accumulation. The study demonstrated that different metals originated from different anthropogenic sources, with Cu mainly associated with agricultural practices [81].

Morocco

Copper contamination in Morocco has been associated with abandoned mining sites affecting surrounding agricultural soils. At the Bir Nehass mining site, soils and tailings contained very high concentrations of Cu, Zn, Pb and Cd. Copper concentrations reached up to 2892 mg kg^{-1}, decreasing with increasing distance from the mine tailings. Several native

plant species demonstrated high metal accumulation capacity, suggesting their potential use in phytoremediation programs [82].

Democratic Republic of Congo

Copper and cobalt mining activities in the Katanga Province of the Democratic Republic of Congo have significantly affected surrounding environments. Historical and modern mining activities have resulted in metal dispersion into soils, including agricultural areas. Although some agricultural zones showed background-level concentrations, areas influenced by mining waste and processing activities exhibited elevated metal concentrations. The study emphasized the importance of environmental monitoring and remediation around mining operations [83].

Ethiopia

In Ethiopia, metal accumulation in agricultural soils and crops has been investigated in Dawunt Woreda. Soil and lentil samples were analyzed for potentially toxic elements. Mean Cu concentrations were 40.0 mg kg^{-1} in soil and approximately 5.7 mg kg^{-1} in lentils. Pollution indices indicated moderate Cu contamination, while Cd was identified as the principal concern. The cited health-risk assessment found no significant risk to local populations from lentil consumption or soil exposure under the assumptions applied in that study [84]. This finding should not be interpreted as evidence of zero risk under all exposure conditions or as directly applicable to other populations and locations.

Kenya

Copper and zinc enrichment in Kenyan agricultural soils has been evaluated using different geochemical background values. Agricultural soils near Mau and Aberdare forests showed variable Cu enrichment depending on the reference element used. The study demonstrated the importance of selecting appropriate local background values when assessing Cu contamination. Geo-accumulation indices indicated that soils ranged from unpolluted to moderately polluted [85].

Namibia

Copper contamination in Namibia has been strongly linked to mining waste. Around the Kombat tailings dam, agricultural soils were affected by dispersion of mine residues through wind and water erosion. Copper concentrations in tailings reached 9086 mg kg^{-1}, while surrounding agricultural soils contained up to 150 mg kg^{-1} Cu. Contamination indices indicated severe Cu pollution, although sequential extraction showed that Cu was mainly associated with less mobile soil fractions [86].

Americas

Mexico

In Mexico, copper pollution has been documented around mining regions. At the Concepción del Oro mining district, historical mining activities resulted in dispersion of Cu-rich tailings into surrounding agricultural soils. Copper concentrations reached levels up to 100 times higher than local background values. Extraction tests indicated that part of the Cu fraction could become mobilized through biological activity, creating potential risks for groundwater and food-chain contamination [87].

Chile

Copper contamination in Chilean agricultural soils has been associated with emissions from copper smelting activities. In the Puchuncaví valley, continuous operation of a copper smelter resulted in acidic soils enriched with Cu and other contaminants. Phytostabilisation strategies using amendments such as seashell grit and zeolite reduced Cu mobility and

improved soil conditions, showing potential for remediation of contaminated agricultural areas [88].

Ecuador

In Ecuador, agricultural soils affected by mining activities have shown elevated trace metal concentrations. In Ponce Enriquez, one of the country's major gold mining regions, farmland soils contained increased levels of As, Cr, Cu and Ni. Several crops exceeded permissible limits for trace elements, creating potential risks for consumers. Health risk assessment indicated possible carcinogenic and non-carcinogenic effects associated with long-term consumption of contaminated crops [89].

Recent research evaluating ecological and health risks associated with Pb, Cd, As, and Cu contamination in agricultural soils in arid regions provides additional context for site-specific risk assessment [90]. Such work is relevant because the presence of multiple potentially toxic elements can complicate the attribution of ecological effects and estimated health risks to an individual metal. In interpreting these findings, the contribution of Cu should be considered alongside its concentration, chemical availability, soil characteristics, and relevant exposure pathways. Results from arid-region soils should not be transferred directly to other agricultural settings without considering differences in soil chemistry, climate, land use, and exposure conditions.

3.2.3. Analytical Methods Reported for the Determination of Copper Pollution in Agricultural Soils

The reviewed studies showed that copper pollution in agricultural soils is determined using a wide range of analytical methods, including chemical extraction procedures, spectrometric techniques, electrochemical methods, and advanced spectroscopic approaches. These methods differ in their ability to measure total Cu concentration, Cu fractions, mobility, and spatial variability.

Sequential extraction methods were applied to evaluate the chemical forms and mobility of Cu in soils. Akkus et al. [91] used a five-step sequential extraction procedure to separate Cu into exchangeable, organically bound, carbonate-bound, Fe/Mn oxide-associated, and residual fractions. The extracted fractions were measured using inductively coupled plasma optical emission spectrometry (ICP-OES). The study reported Cu concentrations between 23 and 72 mg kg^{-1}, with the exchangeable fraction representing 0.42–2.53% of total Cu.

Spectrometric methods based on plasma and atomic absorption techniques were frequently used for Cu quantification. Gunkel et al. [92] compared ion chromatography (IC), anodic stripping voltammetry (ASV), adsorptive stripping voltammetry (AdSV), ICP atomic emission spectroscopy (ICP-AES), and atomic absorption spectroscopy (AAS) for determining heavy metals in Cu-contaminated agricultural soils. The results showed good agreement between ICP-AES and IC measurements for Cu, Zn, Ni, and Mn determination.

Da Silva et al. [93] applied ultrasound-assisted extraction combined with flame atomic absorption spectrometry (FAAS) for Cu determination in agricultural soil samples. The optimized extraction procedure provided efficient metal recovery using a reduced volume of acid mixture. The method was combined with contamination indices, including the geoaccumulation index (Igeo), enrichment factor (EF), contamination factor (CF), and pollution load index (PLI), to evaluate soil contamination levels.

Portable analytical techniques have been investigated as alternatives to conventional laboratory analysis. Caporale et al. [94] assessed portable X-ray fluorescence (pXRF) for determining aqua regia-extractable Cu concentrations in agricultural soils. Strong correlations between pXRF and laboratory measurements were reported, with R^2 values

above 0.90 for Cu and several other metals, demonstrating the suitability of pXRF for rapid soil analysis.

Spectroscopic methods provided non-destructive approaches for estimating Cu concentrations. Antonucci et al. [57] developed a hyperspectral imaging method using visible–near-infrared and near-infrared spectral regions. Partial least squares regression models were used to predict Cu concentrations, achieving correlation coefficients of 0.93 for visible–near-infrared and 0.77 for near-infrared measurements.

Terahertz spectroscopy was also evaluated for heavy metal detection in soils. Li et al. [95] investigated terahertz time-domain spectroscopy for soils contaminated with Cu^{2+} and other heavy metals. Different absorption characteristics were observed within the 0.1–1.1 THz range, indicating that terahertz techniques may be useful for future rapid detection.

Plant-based optical measurements were studied as indirect indicators of Cu contamination. Qu et al. [96] analyzed solar-induced fluorescence responses in crops exposed to Cu stress. Reflectance measurements obtained using an ASD Fieldspec spectrometer showed changes in fluorescence characteristics, and far-red fluorescence was positively related to Cu concentration in plant tissues.

Yang et al. [56] developed an ensemble learning model combining spectral preprocessing, principal component analysis, and several regression algorithms. The stacking model achieved improved prediction performance with $R^2 = 0.77$, RMSE = 7.65 mg kg^{-1}, and RPD = 2.29.

Several studies combined analytical measurements with statistical modelling for improved interpretation of soil contamination. Anaman et al. [97] integrated principal component analysis (PCA), positive matrix factorization (PMF), and geographic information system (GIS) mapping. Chen et al. [98] combined UNMIX, PMF, and Pb-Zn-Cu isotope analysis with chemical measurements, while Cao et al. [99] applied PMF with isotope fingerprinting to improve identification of contamination patterns.

3.2.4. Impacts of Copper Contamination on Agricultural Soil Properties, Microbial Communities, and Nutrient Cycling

Effects of Copper Contamination on Agricultural Soil Microbial Communities

Copper contamination has been shown to significantly influence the structure, diversity, and functional capacity of microbial communities in agricultural soils. Studies conducted in Cu-polluted agricultural soils from the Valparaiso region of central Chile demonstrated that long-term copper exposure resulted in the selection of Cu-resistant bacterial populations. Although DGGE analysis showed similar bacterial community patterns between Cu-polluted and non-polluted soils, Cu-resistant bacteria were more abundant in contaminated soils. The presence of *copA* genes, encoding copper resistance-related multicopper oxidases, was detected in polluted soils but not in uncontaminated soils. Several resistant isolates belonging to *Sphingomonas*, *Stenotrophomonas*, and *Arthrobacter* exhibited high copper tolerance and carried genetic determinants associated with Cu resistance [46].

Copper contamination also altered rhizosphere microbial communities in agricultural fields affected by industrial activities. Analysis of Cu-contaminated agricultural soils in Gujarat, India, revealed reduced microbial diversity under Cu stress conditions. Cu-tolerant bacterial communities were dominated by genera such as *Enterobacter* and *Pseudomonas*. Several isolated Cu-tolerant bacteria demonstrated plant growth-promoting properties, and *Enterobacter* sp. P36 reduced copper accumulation in mung bean roots while improving plant growth under Cu stress conditions [43].

Long-term copper exposure has also been associated with changes in the abundance and mobility of antibiotic resistance genes (ARGs) in agricultural soils. In soils exposed to

4–5 years of Cu contamination, the abundance and diversity of ARGs increased, with the strongest responses occurring at medium to high Cu concentrations depending on soil type. The relationship between ARGs, microbial taxa, and mobile genetic elements suggested that copper contamination can promote the spread of resistance traits through microbial communities [55].

Effects of Copper Contamination on Soil Nutrient Cycling

Copper contamination strongly affects microbial processes involved in nitrogen cycling. Experimental studies using different soil types demonstrated that increasing Cu concentrations reduced the abundance of important nitrogen-cycling microorganisms, including ammonia-oxidizing archaea and *Nitrospira* nitrite-oxidizing bacteria. These microbial changes were associated with decreased potential ammonia oxidation rates and reduced plant biomass after long-term Cu exposure [100].

A global meta-analysis confirmed that copper contamination significantly disrupts soil nitrogen transformations. Copper addition or Cu-polluted soils reduced potential nitrification by 33.8%, mainly due to decreased nitrification enzyme activity, microbial biomass, and ammonia-oxidizing archaeal abundance. The inhibition of nitrification became stronger when Cu concentrations exceeded 150 mg kg^{-1}, while lower concentrations could temporarily stimulate nitrate production [101].

In Cu and Cd co-contaminated agricultural soils, metagenomic analysis showed that heavy metal stress altered microbial functional genes related to nitrogen cycling. Contamination stimulated nitrification, denitrification, and dissimilatory nitrate reduction processes through enrichment of *Nitrospira*, while nitrogen fixation was reduced due to decreases in specific microbial groups such as *Desulfobacca*. These changes indicate potential disruptions in nitrogen availability and increased risk of nutrient imbalance in agricultural systems [102].

Copper Accumulation and Distribution in Agricultural Soils

Copper contamination is strongly influenced by agricultural practices and soil properties. In vineyard soils, high concentrations of total copper and available Cu fractions were detected, with mean total Cu concentrations reaching 368 mg kg^{-1}. Exchangeable and potentially available copper fractions were associated with soil properties such as pH and organic carbon content. Copper distribution was also affected by planting patterns, with higher accumulation observed along cultivated rows due to repeated agricultural inputs [103].

Copper-contaminated soils near mining areas frequently exhibit strong acidity, which affects Cu mobility and plant availability. Interactions between copper and other soil factors, including aluminum toxicity, influence copper uptake by plants. Studies using maize demonstrated that Al co-stress reduced Cu absorption and translocation by modifying root surface properties and altering metabolic responses related to stress adaptation [104].

3.2.5. Effects of Copper Contamination on Crop Growth, Metal Uptake, and Plant Responses

Effect of Copper Contamination on Plant Growth and Physiological Processes

Copper is an essential micronutrient involved in photosynthesis, respiration, and enzyme activity. However, excessive Cu exposure can impair plant growth and development. The severity of these effects depends on plant species, developmental stage, Cu concentration, and exposure conditions.

Heavy metal stress, including Cu toxicity, has been shown to reduce crop productivity by affecting germination, biomass production, and physiological processes. Athar et al. [105] reported that heavy metal exposure significantly reduced wheat (*Triticum aestivum* L.)

growth and grain yield, with Cu being among the most toxic metals tested. Metal exposure also decreased nitrogen content and grain protein concentration, indicating negative effects on nutritional quality. Similarly, Houshmandfar [106] found that increasing concentrations of mixed heavy metals containing Cu, Cd, Ni, and Zn reduced safflower germination, shoot growth, root development, and biomass production.

The influence of Cu stress has also been observed in vegetable crops. Alamer et al. [107] reported that heavy metal exposure reduced yield components of tomato (*Solanum lycopersicum*) and eggplant (*Solanum melongena*), together with reductions in photosynthetic pigments and increases in antioxidant enzyme activity, demonstrating activation of plant defense mechanisms under metal stress.

In cereal crops, Cu contamination affected both growth and metal distribution. Deng et al. [108] showed that Cu pollution reduced wheat growth, while night warming partially alleviated growth inhibition by increasing straw, spike, aboveground, and total biomass. However, warming also altered Cu uptake patterns, potentially increasing the risk of Cu accumulation in edible plant tissues.

Copper stress responses are also related to changes in plant metabolism. Rob et al. [51] described that excessive Cu accumulation in rice disrupts germination, growth, photosynthesis, and cellular processes, leading to oxidative stress. Plants respond through defense mechanisms such as antioxidant activity, metal chelation, and compartmentalization.

Copper Uptake and Accumulation in Agricultural Crops

Plants differ greatly in their ability to absorb and accumulate Cu. Uptake depends on plant species, tissue type, growth stage, and exposure conditions.

Vegetable crops grown in contaminated environments showed increased Cu accumulation compared with plants cultivated in less polluted areas. Ai et al. [109] demonstrated that Chinese cabbage and radish accumulated higher concentrations of Cu, Zn, and Cd when grown on polluted farmland. Metal uptake changed throughout plant development, with different accumulation patterns depending on the vegetable species and growth stage.

The movement of Cu within plants varies between roots, stems, leaves, and edible organs. Li et al. [110] investigated plants growing near electronic waste-contaminated farmland and found that several species accumulated Cu mainly in roots, while some species showed stronger translocation toward leaves. These differences indicate that plants have different mechanisms controlling Cu transport and storage.

In tomato and eggplant, Cu was detected in fruits, and its concentration increased with greater metal exposure. Alamer et al. [107] reported the accumulation of Cu, Ni, Zn, and other metals in edible tissues. These findings demonstrate that metals can be transferred to edible plant parts under the investigated conditions. However, detection or accumulation in edible tissues does not, by itself, establish that consumption poses a health risk. Risk characterization requires consideration of the measured concentrations, applicable food-safety limits, consumption rates, and estimated dietary exposure. Napoli et al. [111] found differences in Cu distribution among plant species and tissues: tomato accumulated Cu in roots and fruits, whereas spinach and *Ricinus* accumulated greater amounts in aboveground tissues, particularly leaves and stems.

Crop selection can influence metal accumulation in food products. He et al. [112] evaluated rice cultivars and found significant differences in Cu accumulation in grains. Certain cultivars showed lower Cu accumulation capacity and may be more suitable for cultivation in areas affected by metal contamination.

Qiu et al. [113] demonstrated similar variation among Chinese flowering cabbage cultivars. Some cultivars accumulated lower concentrations of heavy metals and were identified

as pollution-safe cultivars, suggesting that plant selection can reduce risks associated with contaminated agricultural production.

Copper Translocation and Effects on Food Safety

The transfer of Cu from roots to aboveground tissues can influence the concentrations measured in edible plant parts and is therefore relevant to food-safety assessment. The implications for human exposure depend on the concentrations in the consumed tissues, the amount consumed, and the contribution of other dietary sources.

In wheat, Deng et al. [108] observed that Cu pollution changed metal transport between roots, stems, leaves, and spikes. Environmental conditions influenced Cu movement, showing that plant responses to contamination may change under future climate scenarios.

Rice cultivated in mining-affected regions has been investigated for the accumulation of potentially toxic elements in grains. Pu et al. [114] reported elevated concentrations of Cu and other metals in rice systems near copper-mining areas. These observations identify a potential pathway for dietary exposure; however, the magnitude of any associated health risk depends on the measured concentrations and the results of an appropriate dietary-exposure and risk assessment.

Similarly, Simonovic et al. [44] investigated Cu and As in wheat grown near a copper-mining area. The distribution of these elements among roots, stems, and grains provided information about their uptake and translocation under the investigated conditions. The presence of metals in grain is relevant to food-safety monitoring, but the implications for consumers should be assessed using the measured grain concentrations, applicable regulatory limits, and estimated dietary exposure rather than inferred from detection alone.

Sweet potato has also been investigated as a metal-accumulating crop. Noviardi et al. [115] showed that sweet potato grown on soils containing mine tailings accumulated heavy metals, including Cu, with higher concentrations in shoots than roots. Although this property may support phytoremediation, contaminated plants may not be suitable for consumption.

Plant Tolerance and Phytoremediation Approaches

Some plant species tolerate moderate Cu concentrations and may contribute to remediation strategies. Avkopashvili et al. [116] studied sugar beet growing near mining areas and found that bio-stimulant treatments reduced Cu, Cd, and Zn accumulation while improving plant development and lifespan.

Microorganisms can improve plant performance under Cu stress. Rojas-Tapias et al. [117] demonstrated that inoculation of maize with plant growth-promoting bacteria increased biomass, chlorophyll content, and Cu extraction capacity. Bacterial treatments improved plant tolerance and enhanced phytoremediation potential.

Plant responses may also depend on Cu concentration. Lajayer et al. [118] observed that low Cu levels improved growth, nutrient status, and essential oil production in pennyroyal (*Mentha pulegium* L.), suggesting that some plants can tolerate mildly contaminated conditions.

However, not all crops can resist Cu stress. Kucharski [119] reported that Cu contamination negatively affected spring barley growth and reduced microbial activity, while bacterial inoculation did not completely remove the negative effects of Cu toxicity.

3.2.6. Copper and Multi-Metal Contamination Characteristics of Agricultural Soils

Heavy Metal Contamination Patterns in Copper-Polluted Agricultural Soils

The reviewed studies indicate that copper contamination in agricultural soils rarely occurs as an isolated problem and is frequently associated with multiple heavy metals.

Agricultural soils affected by anthropogenic activities such as mining, smelting, wastewater irrigation, and intensive agriculture commonly contain combinations of Cu, As, Cd, Cr, Ni, Pb, Zn, and other potentially toxic elements.

In Qatar agricultural soils, the investigated metals showed a concentration pattern of Zn > Cr > V > Ni > As > Cu > Pb > Cd. Although copper concentrations were lower than several other metals, Cu was still associated with anthropogenic inputs. Elements including As, Cr, Ni, and Zn exceeded average global background concentrations, and enrichment factors indicated human-related sources. The pollution indices showed that some agricultural soils were contaminated, with pollution load index values above 1 and geo-accumulation index values indicating different degrees of pollution [120].

Studies near copper smelting areas demonstrated stronger Cu accumulation. In paddy soils surrounding a copper smelting plant in southern China, Cu, Zn, Pb, and Cd were mainly influenced by anthropogenic activities, while Ni, Co, and Cr were more closely related to geological sources. Copper showed increased mobility compared with uncontaminated soils, with the mobility sequence reported as Zn > Cd > Cu > Pb, indicating that Cu represented a potential environmental concern due to its availability in soil fractions [55].

Agricultural soils impacted by industrial activities also showed elevated copper levels together with other metals. In Tavşanlı district, Turkey, the mean Cu concentration was 32.89 mg kg^{-1}, while Cr, Co, Mn, and Ni also showed elevated concentrations compared with background values. Contamination factor, enrichment factor, and geo-accumulation index analyses identified pollution mainly associated with Co, Cr, and Ni; however, Cu was also detected as part of the metal contamination profile. Statistical analyses suggested that the metals originated from both natural and anthropogenic sources [121].

Influence of Mining and Industrial Activities on Copper Distribution

Mining activities are an important documented source of Cu contamination in agricultural environments. At the Bookook Mine area in Korea, mine waste and drainage were investigated as sources of contamination affecting surrounding farmland. The reported concentrations of metals in mine soils followed the order Zn > Ni > Cu > As > Cd > Pb. The findings indicate that mining-related contamination may affect agricultural soils and create potential pathways for environmental and human exposure. However, the magnitude of any health risk cannot be established from the presence of Cu in soil alone; it depends on metal concentrations in relevant exposure media, bioavailability, exposure pathways, and the results of a site-specific risk assessment [122].

In Dabaoshan, Guangdong Province, agricultural fields irrigated with acid mine wastewater showed substantial multi-metal contamination. A high proportion of soil samples exceeded the applicable agricultural safety limits, with 94.9% exceeding the reported Cu limit, followed by exceedances for Cd, Pb, As, Cr, and Zn. Metals were also detected in vegetables, demonstrating their transfer to edible plant tissues under the investigated conditions. The health-risk assessment reported that As, Cr, and Cd contributed most strongly to the estimated risk and that children were more vulnerable to exposure through vegetable consumption [123]. These findings distinguish measured contamination from estimated health risk: the risk conclusions apply to the exposure assumptions and assessment framework used in the cited study.

Long-term contamination from mining waste was also observed in Chenzhou Pb/Zn mining areas. Seventeen years after a tailing dam failure, soils remained highly contaminated with As, Cd, Zn, Pb, and Cu. Contamination levels followed the order GYB > SZY > JTC, indicating that remediation reduced but did not eliminate metal pollution. Copper and other metals accumulated differently depending on crop species, soil

conditions, and metal availability. The bioaccumulation factor of crops followed the order Cd > Zn > Cu > Pb > As [124].

Biological Responses and Remediation Approaches

The reviewed literature shows that microorganisms can influence copper toxicity and availability in contaminated agricultural soils. A copper- and cadmium-resistant endophytic fungus, *Penicillium funiculosum* LHL06, demonstrated high copper biosorption capacity and improved soybean tolerance under Cu stress. Inoculated plants showed increased biomass, improved nutrient uptake, reduced oxidative damage, and enhanced copper removal compared with untreated plants. The study suggests that beneficial microorganisms may contribute to the remediation of Cu-contaminated agricultural soils [125].

3.2.7. Current Approaches for the Remediation of Copper-Polluted Agricultural Soils

Remediation strategies for copper (Cu)-contaminated agricultural soils differ in their mechanisms and intended outcomes, and their effectiveness should be evaluated using distinct indicators. In particular, a reduction in total soil Cu concentration indicates removal or transfer of Cu out of the soil, whereas decreases in dissolved, exchangeable, extractable, or plant-available Cu indicate reduced mobility or bioavailability and do not necessarily demonstrate a reduction in total Cu content. Similarly, lower plant Cu uptake or toxicity may indicate improved biological conditions without substantial removal of Cu from the soil. Accordingly, the approaches reviewed below are distinguished according to whether they primarily immobilize or stabilize Cu, extract or remove Cu, promote plant-assisted removal, or reduce Cu transfer and toxicity through biological processes. Their reported effectiveness is interpreted in relation to the specific endpoint measured, with recognition that experimental conditions, soil properties, contamination levels, and treatment duration may affect their applicability to agricultural fields [126].

Copper Immobilization and Stabilization in Contaminated Agricultural Soils

Immobilization is one of the most frequently investigated approaches for Cu-contaminated agricultural soils because Cu strongly interacts with soil minerals and organic matter. Unlike extraction-based techniques, immobilization generally aims to reduce Cu mobility, bioavailability, leaching, or plant uptake by transferring Cu into more strongly bound or less accessible forms. Consequently, successful stabilization does not necessarily reduce the total Cu concentration in soil; instead, it may reduce exposure and associated toxicity while Cu remains within the treated soil. The effectiveness of these amendments should therefore be interpreted primarily in terms of changes in Cu fractions, leaching, bioavailability, and biological responses, rather than as evidence of Cu removal.

Zeolite-based stabilization has also been investigated. Terzano et al. [127] reported that coal fly ash treatment promoted zeolite formation in Cu-contaminated agricultural soil, strongly decreasing dissolved Cu concentration and increasing the proportion of stabilized Cu in the solid phase. The study showed that Cu was trapped inside newly formed zeolitic structures, mainly as Cu(II) hydroxide and Cu(II) oxide. These findings indicate reduced dissolved Cu and enhanced retention in the solid phase, rather than demonstrated removal of total soil Cu. In a study conducted in Romania, activated bentonite (BacffGS) and natural zeolite from Zalău (Zn(0–0.4)ZL and Zn(1–3)ZL) demonstrated the highest effectiveness in reducing copper mobility [128]. This result supports their use as potential immobilizing amendments, but reduced mobility should not be interpreted as a decrease in total Cu concentration unless such a decrease was independently measured.

Organic amendments have shown strong potential for reducing Cu availability. Fatima et al. [105] compared compost, rice husk, rice husk biochar, poultry manure, and

animal manure and found that rice husk biochar produced the greatest reduction in Cu mobility. Similarly, Bashir et al. [129] demonstrated that sesame straw biochar increased Cu adsorption capacity and reduced Cu uptake by *Brassica* plants in wastewater-irrigated soils. These findings indicate enhanced Cu retention and reduced plant exposure, rather than necessarily lower total soil Cu concentrations. Compost and vermicompost also reduced Cu mobility and improved soil fertility, with vermicompost showing higher Cu immobilization efficiency. Such benefits should be distinguished from actual Cu removal, which requires transfer of Cu out of the soil or into a separately recoverable fraction.

Biochar combined with additional functional materials further improved Cu retention or extraction, depending on the treatment and endpoint assessed. Wang et al. [92] developed a biochar–humic acid material that enhanced Cu adsorption by increasing oxygen-containing functional groups, supporting its potential for immobilization rather than demonstrating a reduction in total soil Cu. Saah and Nagpal [130] reported that a groundnut shell carbon quantum dot–zinc ferrite nanocomposite removed more than 80% of Cu from polluted soils and extracted Cu from exchangeable, carbonate, oxide/hydroxide, organic, and residual fractions. This result represents a removal-related endpoint, distinct from adsorption or redistribution among soil fractions. However, the reported percentage should be interpreted in relation to the study's experimental conditions and measurement basis before extrapolating its effectiveness to field-scale agricultural remediation.

Modified biomaterials have also been studied. Shaghaleh et al. [131] developed TEMPO-cellulose/lignin/acrylamide-based hydrogel systems capable of reducing Cu bioavailability by more than 70% in contaminated soils. The hydrogel reduced Cu toxicity through adsorption, complexation, ion exchange, and formation of stable metal-binding structures. This percentage refers to reduced bioavailability, not necessarily to a comparable decrease in total soil Cu. Li et al. [64] reported that cysteine-modified chitosan selectively stabilized Cu by converting bioavailable Cu fractions into stable forms while preserving soil microbial properties. These findings suggest that modified biomaterials can reduce Cu accessibility and associated biological risks, although stabilization alone does not demonstrate net removal of Cu from the treated soil.

Mineral and carbon-based amendments have also shown benefits for plant growth. Shaheen et al. [58] found that activated charcoal, peat, aluminum oxide, compost, phosphate rock, and zeolite reduced soluble Cu fractions and decreased Cu accumulation in maize. Activated charcoal was the most effective organic amendment, while aluminum oxide was the most efficient inorganic material. These outcomes indicate reduced Cu solubility and plant accumulation under the investigated conditions, rather than necessarily reduced total soil Cu. Thus, amendment performance should be assessed using the specific indicators reported, including soluble or extractable Cu, plant uptake, and plant growth responses.

Soil Washing and Chemical Extraction Methods

Unlike immobilization, soil washing and chemical extraction aim to transfer Cu from the soil into an extractant or liquid phase, potentially enabling its subsequent recovery or disposal. Their performance should therefore be assessed using the amount or proportion of Cu extracted from the soil, together with changes in residual soil Cu and the characteristics of the resulting waste stream. A decrease in an extractable Cu fraction alone does not necessarily demonstrate a reduction in total soil Cu unless Cu has been transferred out of the soil and the mass balance supports this conclusion.

Copper extraction has been explored when stabilization alone does not meet remediation objectives. Electrokinetic remediation (EKR) has shown potential for mobilizing Cu in agricultural soils where the metal is strongly retained. Navas-Higuero et al. [54] demonstrated that EDTA and EDDS enhanced Cu migration during electrokinetic treatment

through the formation of soluble Cu complexes. More than 20% Cu extraction was achieved from agricultural soil contaminated by copper-based fungicides. This result provides a quantitative removal-related endpoint, although the percentage extracted does not by itself establish the final residual Cu concentration, the proportion of Cu remaining in the soil, or the suitability of the treated soil for agricultural use.

Soil washing using chelating agents has also been studied. Race et al. [132] reported that EDDS extraction removed exchangeable and reducible Cu fractions from contaminated soils, with intraparticle diffusion controlling the extraction process. The reported changes concern specific Cu fractions and should not automatically be interpreted as equivalent reductions in total soil Cu. Natural humic substances were proposed as alternatives to synthetic chelators. Borggaard et al. [133] showed that humic substances extracted considerable amounts of Cu while reducing environmental concerns associated with EDTA. The practical performance of these approaches depends on the amount of Cu transferred into the extractant, the residual soil Cu concentration, and the management of Cu-containing extraction solutions.

Dumbrava et al. [48] investigated horse manure as a natural chelator source and demonstrated improved Cu bioavailability and uptake by white mustard, suggesting that organic chelators may enhance phytoextraction while increasing plant biomass. However, increased Cu availability and plant uptake represent intermediate steps toward removal rather than evidence of completed remediation. Net Cu removal depends on the amount of Cu accumulated in harvestable plant biomass and its subsequent removal from the site; any increase in Cu mobility without sufficient plant uptake or extraction could instead increase the risk of Cu leaching.

Phytoremediation and Plant-Assisted Cu Removal

Phytoremediation can contribute to agricultural soil recovery through two distinct pathways: phytoextraction, in which Cu is taken up into harvestable plant tissues and removed from the site, and phytostabilization, in which plants and their associated soil processes reduce Cu mobility, erosion, or exposure without necessarily decreasing total soil Cu. Plant tolerance, biomass production, Cu concentration in plant tissues, and the amount of Cu removed at harvest are therefore complementary but non-equivalent indicators of performance. Evidence of plant growth or Cu accumulation alone is insufficient to establish effective soil decontamination; quantitative assessment of net Cu removal requires consideration of biomass, tissue Cu concentration, harvest frequency, and the residual soil Cu concentration.

Sunflower has been widely investigated. Shah et al. [134] found that IAA and EDTA improved Cu accumulation and plant growth in sunflower and maize, with IAA producing stronger enhancement than EDTA. These results suggest improved plant performance and Cu uptake, but do not establish the amount of Cu removed from the soil without corresponding data on harvested biomass and its Cu content. However, Cicatelli et al. [135] reported that assisted phytoremediation using EDTA and EDDS was limited because Cu remained poorly available and extraction occurred slowly. Together, these studies illustrate that enhanced plant growth or Cu uptake does not necessarily translate into rapid or substantial reductions in total soil Cu.

Sunflower growth and Cu tolerance were also improved through microbial associations. Meier et al. [136] showed that arbuscular mycorrhizal fungi (AMF) increased sunflower biomass and promoted Cu binding through glomalin accumulation. Cornejo et al. [47] confirmed that AM fungi increased Cu-bound soil proteins, allowing immobilization of a substantial proportion of soil Cu. These findings support a role for AMF in improving plant tolerance and Cu retention in soil. Nevertheless, enhanced biomass and Cu binding

should be interpreted as evidence of improved biological performance or immobilization, respectively, rather than direct evidence of net Cu removal.

Other crops also showed phytoremediation potential. *Brassica nigra* and *Brassica juncea* accumulated Cu in shoots while maintaining tolerance, suggesting suitability for contaminated agricultural fields [137]. Shoot accumulation provides a basis for phytoextraction, but the amount of Cu removed depends on harvestable biomass and tissue Cu concentrations. Kenaf improved Cu uptake and physiological performance after phosphorus addition in highly contaminated mining soils [138]. Cumbane et al. [139] showed that kenaf could tolerate contaminated soils and remove Cu, although growth depended strongly on climatic conditions. These studies indicate potential for plant-assisted Cu removal, while also highlighting the importance of biomass production and environmental conditions when evaluating practical remediation efficiency.

Jute varieties C-3 and HT demonstrated strong Cu resistance and accumulated higher Cu concentrations compared with sensitive varieties, making them possible phytoremediation crops [66]. Indian mustard also showed improved Cu removal when nitrogen and phosphorus fertilization increased biomass production [61]. Cu tolerance and tissue accumulation identify potentially useful plant traits, whereas effective phytoextraction additionally requires sufficient harvestable biomass and removal of the Cu-containing plant material. Accordingly, these findings indicate phytoremediation potential but should not be taken as evidence of a particular reduction in total soil Cu unless quantitative removal data are available.

Other plant species have been examined for stabilization rather than extraction. Capuana et al. [90] found that myrtle tolerated Cu-contaminated substrates and was more suitable for re-vegetation than metal removal. Joshi et al. [140] reported that halophytes accumulated several metals, including Cu, and could contribute to phytosequestration in degraded saline soils. Gardezi et al. [141] demonstrated that *Leucaena leucocephala* accumulated Cu and could support bioremediation strategies. These examples illustrate the need to distinguish revegetation and stabilization from phytoextraction: plant tolerance may support the recovery of vegetation cover, while net removal requires Cu accumulation in harvestable tissues followed by their removal from the contaminated site.

Microbial and Biological Enhancement of Remediation

Microbial and biological processes can enhance remediation by modifying Cu availability, supporting plant growth, promoting metal binding, or facilitating Cu uptake. Their effects must be interpreted according to the endpoint measured: reduced plant Cu uptake or transfer may indicate lower exposure, whereas increased plant uptake may support phytoextraction only if the Cu accumulated in harvestable biomass is subsequently removed. Likewise, enhanced microbial binding or changes in soil Cu fractions may indicate immobilization without reducing total soil Cu. Distinguishing these outcomes is essential when comparing biological approaches with techniques designed to extract Cu directly from contaminated soils.

Microbial interactions can improve plant resistance and influence Cu partitioning between soil and plants. Adeyemi et al. [142] reported that AMF inoculation increased soybean growth and reduced Cu transfer from roots to shoots. This response indicates altered Cu distribution and potentially reduced shoot exposure, but does not demonstrate net Cu removal or lower total soil Cu. Fatnassi et al. [88] showed that *Rhizobium* and plant-growth-promoting bacteria reduced Cu uptake and improved antioxidant responses in *Vicia faba*. These results suggest improved plant tolerance and reduced Cu accumulation in plant tissues, rather than enhanced phytoextraction. The remediation value of such microbial

associations therefore depends on whether the objective is to reduce biological exposure, stabilize Cu, or remove it from the soil.

Copper-resistant microorganisms may contribute to natural adaptation in polluted environments. Davalos et al. [143] identified copper-resistant Rhizobiales bacteria containing multiple copper resistance mechanisms, suggesting their potential role in Cu-contaminated agricultural ecosystems. The presence of resistance mechanisms provides evidence of microbial adaptation, but does not by itself demonstrate remediation effectiveness. Such potential requires evaluation through measurable outcomes, including Cu mobility, soil bioavailability, plant responses, or verified Cu removal, depending on the intended application.

Intercropping systems have also improved remediation performance. Bian et al. [144] demonstrated that bamboo and *Sedum* intercropping increased microbial diversity and enhanced removal of Cu, Zn, and Cd compared with monoculture systems. The reported increase in metal removal distinguishes this approach from strategies that primarily immobilize Cu or reduce its bioavailability. However, the magnitude of Cu removal and its implications for agricultural soil recovery should be assessed using the study's quantitative removal measurements and the residual soil Cu concentration.

Limitations of Remediation Approaches

Remediation performance is constrained by differences in Cu binding, bioavailability, soil properties, and the ability of treatment systems to achieve their intended endpoint. A major limitation is that reduced Cu mobility or toxicity does not necessarily correspond to a decrease in total soil Cu. Immobilization can reduce immediate exposure and leaching risks while leaving much of the Cu in place, whereas extraction-based approaches seek to transfer Cu out of the soil but may require additional treatment of Cu-containing residues or solutions. Phytoextraction is further constrained by plant tolerance, biomass production, the duration of treatment, and the quantity of Cu removed at harvest.

Kayser et al. [145] showed that phytoextraction efficiency was insufficient for practical field-scale Cu removal despite using metal-accumulating plants and amendments. This finding highlights the difference between demonstrating Cu uptake and achieving a meaningful reduction in the soil Cu inventory. Fumagalli et al. [146] reported that white lupin improved soil biological properties and metal availability but removed only small amounts of Cu. Improved soil biological conditions and increased metal availability may therefore occur without substantial net Cu removal.

Iron oxide nanoparticles affected Cu mobility but did not significantly reduce Cu accumulation or toxicity in sunflower under high Cu stress [147]. This result further illustrates that changes in Cu mobility do not necessarily produce corresponding improvements in plant Cu accumulation or toxicity. Anekwe [148] demonstrated that biostimulation and bioventing could remove heavy metals, including Cu, from acid mine drainage-contaminated soils, showing potential for biological treatment systems. However, the applicability of this approach to agricultural soils should be assessed in relation to the specific contamination conditions and quantitative Cu removal achieved.

Comparisons among remediation technologies should consequently distinguish at least four outcomes: (i) reduction in total soil Cu through verified removal; (ii) reduction in Cu mobility or extractability; (iii) reduction in plant uptake or transfer to aboveground tissues; and (iv) reduction in Cu-related toxicity or improvement in soil biological properties. These endpoints provide different types of evidence and should not be used interchangeably. Where studies report only changes in Cu fractions, plant responses, or toxicity, the findings should be described in those terms rather than interpreted as proof of total Cu removal. For agricultural applications, technology selection should reflect the remediation objective,

the magnitude and persistence of the observed effect, the potential for Cu remobilization, and the feasibility of implementation under field conditions.

Figure 9 summarizes the key aspects discussed throughout this review, illustrating the sources, environmental behavior, impacts, remediation strategies, management actions, and future research directions related to copper pollution in agricultural soils. Copper enters agricultural systems primarily through mining and smelting activities, industrial emissions, wastewater irrigation, livestock manure, fertilizers, and repeated applications of copper-based pesticides and fungicides. Once introduced into the soil, Cu interacts with soil minerals, organic matter, and iron and manganese oxides, where its mobility and bioavailability are regulated by soil physicochemical properties such as pH, organic matter content, and redox conditions.

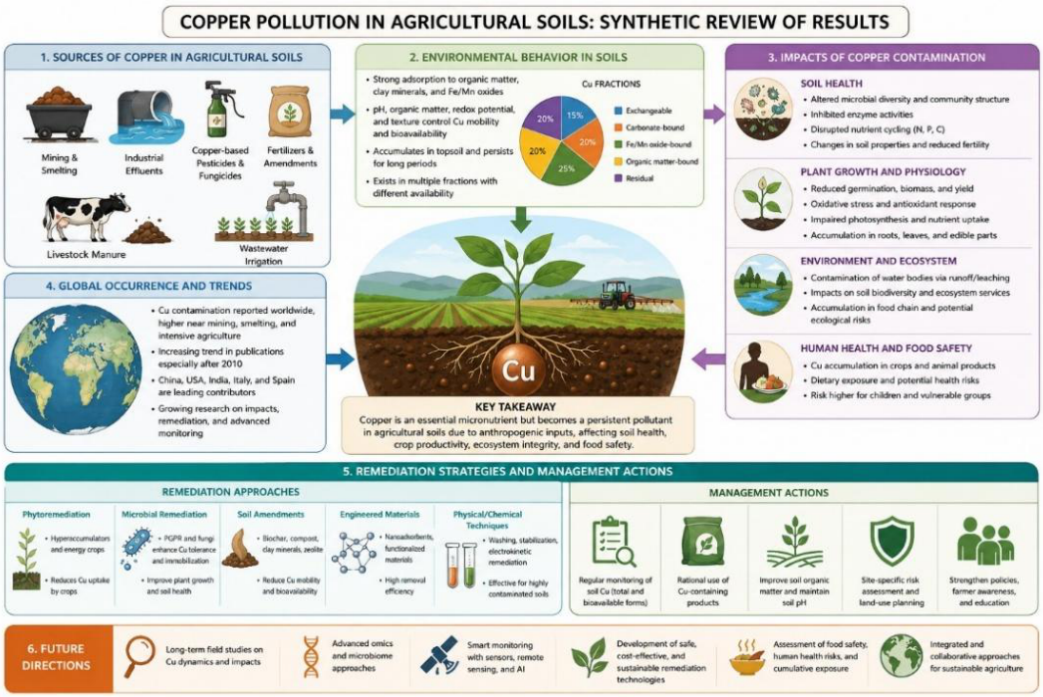


Figure 9. Schematic synthesis of the major findings on copper pollution in agricultural soils.

The figure also summarizes the reported effects of Cu accumulation on soil properties, microbial communities, nutrient cycling, crop growth, and ecosystem functions. It identifies the transfer of Cu into agricultural products as a relevant consideration for food-safety monitoring. The extent of any human-health implications depends on the concentrations measured in edible tissues and on the results of dietary-exposure and risk assessments. The figure also summarizes remediation approaches, including phytoremediation, microbial-assisted remediation, soil amendments, biochar, engineered materials, and physicochemical technologies, together with management measures intended to limit excessive Cu accumulation. Future research priorities include long-term field monitoring, improved analytical methods, evaluation of remediation performance under field conditions, and integrated management practices to reduce environmental risks while maintaining agricultural productivity and soil health.

4. Discussion

4.1. Bibliometric Review

The majority of publications in the dataset were original research articles, followed by review papers, conference proceedings, and book chapters. Publication output was higher

in recent years, particularly after 2020. This pattern may reflect several factors, including changes in scientific publishing activity, research capacity, and interest in environmental contamination and its agricultural implications. However, the bibliometric data do not allow the relative contribution of these factors to be quantified.

China ranked first in publication output, while the United States ranked fourth. These patterns are consistent with the distribution of contributions observed in the analyzed dataset and with the findings of previous studies. Differences in publication output may be associated with research capacity, institutional resources, funding, and national research priorities, but these explanations cannot be confirmed from publication counts alone. Similarly, the presence of substantial mining activities in countries such as Chile, India, and Pakistan may provide a relevant research context, but publication output does not establish the extent of copper contamination in those countries. Direct comparisons of contamination severity require comparable environmental measurements and sampling designs.

The increasing concern regarding the environmental issues associated with elevated copper concentrations in agricultural soils is reflected by the predominance of environmental journals publishing research on this topic, including Science of the Total Environment, Environmental Science and Pollution Research, Environmental Pollution, Journal of Environmental Management, Environmental Geochemistry and Health, and Environmental Monitoring and Assessment. Bibliometric analysis of author keywords provides valuable insights into the main research themes addressed by the scientific community. The keyword analysis likewise highlights the strong emphasis placed on pollution and remediation, as evidenced by the frequent occurrence of terms such as accumulation, contamination, pollution, and phytoremediation.

4.2. Current Challenges and Perspectives in the Management of Copper-Polluted Agricultural Soils

The reviewed literature demonstrates that copper pollution in agricultural soils represents a complex environmental problem influenced by chemical processes, biological responses, and agricultural practices. The diversity of investigated topics indicates that the impact of copper cannot be evaluated only through total soil concentrations, as copper behavior depends on its chemical forms, mobility, soil properties, and interactions with plants and microorganisms [50,55].

Studies addressing microbial communities emphasize that copper contamination may alter soil biological functions by selecting resistant microorganisms and modifying microbial structures. Although copper-resistant bacteria may contribute to adaptation processes and have potential applications in remediation, changes in microbial communities may influence important soil functions such as nutrient cycling and ecosystem stability [43,46]. The relationship between metal contamination and other microbial traits, such as antibiotic resistance, represents an additional concern in agricultural environments [45].

Plant-related studies show that copper contamination has a dual significance. Copper is an essential micronutrient, but excessive concentrations can cause toxicity, reduce plant development, and increase the risk of metal transfer into the food chain. Research on different plant species suggests that tolerance mechanisms and metal accumulation capacity may be useful for phytoremediation; however, the efficiency of plant-based approaches depends strongly on plant species, soil conditions, and copper availability [60,61,66].

The use of microorganisms and amendments has emerged as an important direction for reducing copper risks. Biological approaches, including the use of mycorrhizal fungi and plant-growth-promoting microorganisms, may improve plant tolerance and support contaminated soil recovery [57,59]. At the same time, amendment-based strategies aim to decrease copper mobility and bioavailability through immobilization processes. Materials such as biochar, mineral additives, and modified organic compounds have shown potential,

although their effectiveness depends on contamination characteristics and long-term soil interactions [48,62,65].

Environmental risk assessment should distinguish between the identification of soil contamination and the demonstration of adverse effects or exposure-related risks. For example, studies of contaminated sites affected by uncontrolled waste disposal have highlighted the importance of evaluating soil contamination together with potential environmental transport pathways and associated human-health concerns [149]. Although such evidence is not specific to agricultural Cu contamination, it supports the broader principle that contaminant concentrations should be interpreted in conjunction with site characteristics, relevant exposure pathways, and appropriate risk indicators. Accordingly, findings from studies of other contaminants or land-use settings should be used as methodological context rather than as direct evidence of Cu-specific risks in agricultural soils.

Evidence from agricultural soils in Central Saudi Arabia further illustrates the value of combining heavy-metal measurements with toxicity and health-risk assessment. Such assessments provide a broader basis for evaluating contamination than concentration measurements alone, particularly when several potentially toxic elements occur together [141]. For Cu-contaminated agricultural soils, this approach supports the separate evaluation of total and available Cu, crop accumulation, relevant exposure pathways, and site-specific ecological or human-health risk indicators. The contribution of Cu should also be distinguished from that of co-occurring metals rather than inferred from a combined contamination index alone.

The interpretation of ecological and human-health risks requires a clear distinction between contamination indicators, biological-effect measurements, and exposure-based risk estimates. Total soil Cu concentration is useful for characterizing contamination and comparing results with applicable soil-quality criteria, but it does not independently establish the degree of biological harm or human exposure at a particular site. Ecological assessment should consider, where available, Cu speciation or bioavailable fractions, soil pH, organic matter, relevant soil biological indicators, plant responses, and potential transfer to water or other environmental compartments. Human-health assessment should additionally consider Cu concentrations in edible plant tissues or other relevant exposure media, estimated intake, exposure frequency and duration, and the characteristics of the exposed population. Where studies report contamination indices or modeled hazard and risk estimates, these results should be interpreted according to the parameters and assumptions used. This distinction is particularly important in multi-metal contamination, where the combined risk may reflect the contributions of several elements rather than Cu alone [86,95,126,128,129].

The development of advanced remediation technologies indicates the need for solutions suitable for different contamination scenarios. While extraction-based methods may directly reduce copper concentrations, stabilization approaches may represent a more practical option for agricultural soils where maintaining soil functions is essential [54,64]. Therefore, remediation decisions require consideration of contamination intensity, soil properties, crop production requirements, and environmental risks.

The increasing application of hyperspectral analysis and predictive models suggests a transition toward more efficient monitoring of contaminated agricultural areas. These approaches may provide rapid screening methods and complement traditional laboratory measurements, especially for large-scale assessments [56,57].

A major challenge identified among the reviewed studies is the difficulty of directly comparing results due to differences in contamination sources, soil characteristics, experimental designs, and evaluation criteria. Future research should integrate chemical measurements, biological indicators, and remediation performance assessments to develop more reliable strategies for the sustainable management of copper-contaminated agricultural soils.

The comparison of remediation studies indicates that the effectiveness of a treatment depends on the intended remediation endpoint, soil properties, initial Cu concentration, Cu speciation, treatment duration, and experimental conditions. Immobilization and stabilization treatments primarily reduce Cu mobility, extractability, or bioavailability, whereas extraction-based approaches seek to transfer Cu from the soil into a recoverable phase. Phytoextraction additionally depends on plant tolerance, Cu accumulation in harvestable tissues, biomass production, and the removal and safe management of contaminated biomass. Microbial-assisted approaches may improve plant growth, modify Cu distribution, or promote immobilization and extraction, but these outcomes should be evaluated separately. Consequently, reported percentage reductions cannot be compared directly when studies measure different parameters, such as total soil Cu, soluble Cu, exchangeable Cu, plant uptake, or biological toxicity. Laboratory and greenhouse results demonstrate the potential of particular treatments under the conditions tested but do not, by themselves, establish equivalent effectiveness under field conditions. Comparisons should therefore prioritize the measured endpoint, treatment duration, residual Cu concentration, potential secondary effects, and evidence of sustained performance under agricultural field conditions.

4.3. Comparative Analysis of Copper Contamination in Agricultural Soils Across Countries

Copper contamination in agricultural soils reflects different contamination sources, environmental conditions, and land management practices. The reviewed case studies indicate four principal source categories: copper-based fungicides, industrial emissions and smelting, mining activities, and other anthropogenic inputs, including irrigation and urban activities. These sources differ in their contribution to soil Cu accumulation, its mobility and persistence, and the resulting environmental risks. Table 4 synthesizes the main patterns identified in the reviewed studies.

The comparison shows that contamination source is a major factor determining the distribution and persistence of Cu in agricultural soils. Repeated applications of copper-based fungicides are particularly important in vineyards, where long-term inputs can produce substantial accumulation even after agricultural management changes. Industrial emissions and smelting contribute to contamination through atmospheric deposition and the transfer of metals to surrounding soils, whereas mining activities generate localized hotspots through the dispersion of tailings and mining wastes.

Total Cu concentrations alone do not provide a complete assessment of environmental risk. The reviewed studies indicate that Cu mobility depends on soil properties and chemical speciation, including its association with mineral phases and Fe–Mn oxides. Although relatively stable fractions may limit immediate mobility, they do not eliminate the possibility of long-term environmental effects. Changes in soil pH, organic matter, or redox conditions may alter Cu availability. Consequently, assessments should consider both total concentrations and indicators of Cu mobility and bioavailability.

The principal risks also vary with the contamination source and the receiving environment. In agricultural areas affected by industrial emissions or mining, the transfer of Cu and other potentially toxic elements into crops is an important concern, as illustrated by studies from China and Ecuador [75,79]. In vineyard soils, persistent accumulation may affect soil biological communities, including bacteria and soil fauna [62,69]. These findings support the use of source-specific monitoring approaches that combine chemical measurements with relevant biological and, where appropriate, food-safety indicators.

Management strategies should therefore be matched to the origin and characteristics of contamination. Reducing unnecessary applications of copper-based fungicides can help limit additional accumulation, while industrial emission controls and the stabilization of mine tailings can reduce external inputs. In already contaminated soils, phytoreme-

diation, phytostabilisation, or other suitable remediation approaches may be considered according to Cu bioavailability, contamination severity, and site conditions [72,82,88]. Long-term monitoring should integrate total Cu concentrations, relevant chemical fractions, soil properties, and biological responses to support the protection of soil functions and agricultural productivity.

Table 4. Comparative synthesis of copper contamination in agricultural soils according to source, reported concentrations, mobility, and main environmental risks.

Main Contamination Source	Representative Case Studies	Reported Cu Concentrations or Range (mg/kg)	Mobility and Persistence	Main Environmental Risks
Copper-based fungicides	Croatia, Italy, Georgia [68,69,74]	Croatia: 51.8 in soils under natural vegetation and 199.3 in former vineyard soils; Italy: approximately 1000 in vineyard tree rows, compared with less than 80 in other treatments	Repeated applications promote long-term accumulation, particularly in surface horizons. Mobility depends on soil properties and Cu speciation.	Soil quality deterioration, changes in microbial communities, potential toxicity to soil organisms, and persistence after changes in land use
Industrial emissions and smelting	Germany, Turkey, China, Chile [67,73,75,88]	China: mean of 195.26 in contaminated soils versus 32.84 in reference soils; other studies reported enrichment or contamination without a directly comparable numerical value in the reviewed summaries	Atmospheric deposition and surface accumulation can maintain contamination over long periods. Mobility depends on pH, soil composition, and chemical speciation.	Contamination of agricultural land and crops, adverse effects on soil organisms, and potential human exposure through contaminated food
Mining and mine tailings	Cyprus, India, Iran, Morocco, Namibia, Mexico, Democratic Republic of Congo [71,77,78,82,83,86,87]	Morocco: up to 2892; Namibia: up to 150 in surrounding agricultural soils and 9086 in tailings; Iran: mean of 65.06; Mexico: up to 100 times local background levels	Tailings dispersion by wind and water promotes contamination of surrounding land. Cu may be associated with relatively stable soil fractions, but mobile fractions can remain environmentally relevant.	Long-term soil contamination, potential groundwater and crop contamination, ecological toxicity, and risks associated with food-chain transfer
Irrigation and agricultural inputs	Georgia, Algeria [74,81]	No single comparable Cu range was available in the reviewed summaries; enrichment was associated with irrigation, fungicide use, or agricultural activity	Accumulation depends on the composition of irrigation water, input intensity, soil properties, and the duration of agricultural practices.	Progressive Cu accumulation, deterioration of soil quality, and potential exposure of soil organisms and crops
Urban and mixed anthropogenic sources	Greece, Iraq, Algeria [70,79,82]	Numerical Cu ranges were not available in the reviewed summaries; elevated concentrations or enrichment were reported in affected areas	Mobility and persistence vary with the source, soil characteristics, and association with other soil constituents.	Multi-element soil contamination, potential ecological effects, and reduced suitability of affected land for agricultural production

Note: Concentrations are taken from the reviewed case-study summaries and refer to different soil types, sampling locations, and analytical approaches. Values from agricultural soils, contaminated industrial soils, and mine tailings are not directly equivalent. Where the available summaries did not provide numerical Cu concentrations, no range was inferred. Mobility assessments are qualitative and reflect the reported findings rather than a standardized comparison across studies.

4.4. Evaluation and Comparison of Analytical Methods for Copper Pollution Assessment in Agricultural Soils

The reviewed studies demonstrate that Cu pollution assessment requires analytical methods that combine reliable concentration measurements with information on Cu mobility, spatial distribution, and potential environmental availability. Conventional laboratory techniques remain essential for quantitative determination, whereas rapid screening, spectroscopy, and computational approaches can extend monitoring coverage and improve interpretation.

Sequential extraction provides information beyond total Cu concentrations by distinguishing operationally defined soil fractions with different potential mobility. Akkus et al. [91] demonstrated the value of fractionation for differentiating relatively stable Cu forms from potentially mobile fractions. Although exchangeable Cu may account for a small proportion of total Cu, its determination is relevant to evaluating potential environmental mobility and availability.

Plasma-based techniques, including ICP-OES and ICP-AES, offer sensitive, multi-element determination and remain suitable for laboratory reference measurements. Gunkel et al. [92] reported consistent results for ICP-based Cu determination. Atomic absorption spectroscopy can provide a practical alternative for routine analysis, particularly when combined with efficient sample preparation. Da Silva et al. [93] showed that ultrasound-assisted extraction can reduce preparation time while facilitating Cu analysis. Nevertheless, the performance of these laboratory methods depends on sample digestion, extraction procedures, analytical quality control, and the availability of appropriate equipment.

For field screening, portable X-ray fluorescence (pXRF) can provide rapid measurements and help identify locations requiring detailed laboratory investigation. Caporale et al. [94] demonstrated strong correlations between pXRF measurements and conventional analytical results, although calibration is necessary to account for differences in soil composition and matrix effects. Spectroscopic techniques offer additional opportunities for non-destructive assessment. Antonucci et al. [57] demonstrated the potential of hyperspectral information for estimating Cu concentrations, while Li et al. [110] investigated terahertz spectroscopy for detecting metal contamination. These approaches remain dependent on calibration, soil characteristics, and the ability to distinguish Cu-related signals from interference caused by other soil components.

Machine-learning methods can improve the interpretation of complex spectral datasets. Yang et al. [56] reported increased prediction reliability when multiple algorithms were combined in an ensemble model. However, predictive performance must be evaluated using independent validation data before these models can be considered reliable for wider application. Biological indicators may provide complementary information: Qu et al. [96] showed that fluorescence characteristics change under Cu stress, suggesting potential for vegetation-based monitoring. Such responses are indirect indicators and cannot replace direct measurements of soil Cu.

Finally, multivariate statistics, source-apportionment models, geospatial analysis, and isotope techniques can support the interpretation of contamination patterns. The approaches used by Anaman et al. [8], Chen et al. [76], and Cao et al. [150] illustrate how analytical measurements can be integrated with computational methods to investigate spatial patterns and potential contamination sources.

The principal distinction among these methods concerns the information they provide rather than a single measure of superiority. ICP-based techniques and atomic absorption spectroscopy support quantitative laboratory determination; sequential extraction characterizes operationally defined Cu fractions; pXRF enables rapid screening; and spectroscopic and machine-learning approaches offer opportunities for broader spatial assessment.

Method selection should therefore reflect the monitoring objective, required analytical accuracy, soil characteristics, and available resources. Combining complementary methods can improve assessment reliability, provided that indirect estimates are validated against appropriate laboratory measurements.

4.5. Mechanisms of Copper-Induced Changes in Soil Microbial Communities and Fertility

4.5.1. Microbial Adaptation and Resistance Mechanisms Under Copper Stress

The reviewed studies demonstrate that copper contamination creates strong selective pressure on agricultural soil microbial communities. Long-term exposure does not necessarily eliminate microbial populations but instead promotes the enrichment of organisms with resistance mechanisms. The detection of *copA* genes in Cu-contaminated soils indicates that bacteria can acquire genetic traits allowing survival under elevated copper concentrations. The association of these genes with plasmids in several bacterial isolates suggests that horizontal gene transfer may contribute to the persistence and spread of copper resistance within soil microbial communities [46].

The emergence of Cu-resistant bacteria has important implications for soil functioning because resistance traits may be linked with resistance to other pollutants. Increased abundance of antibiotic resistance genes in Cu-contaminated soils suggests that heavy metal pollution can indirectly influence microbial resistance profiles. The positive association between ARGs and mobile genetic elements indicates that copper contamination may enhance the movement of resistance genes within microbial communities, increasing ecological risks beyond copper toxicity itself [55].

Copper stress also changes the composition of rhizosphere microorganisms. The dominance of Cu-tolerant genera such as *Enterobacter* and *Pseudomonas* suggests that microbial communities adapt by selecting species capable of maintaining metabolic activity under metal stress. Some of these bacteria may provide benefits to plants by improving nutrient availability and reducing Cu uptake, indicating that microbial adaptation can contribute to natural soil recovery processes [43].

4.5.2. Influence of Copper Contamination on Soil Fertility and Nitrogen Cycling

Copper contamination affects agricultural productivity by altering essential microbial processes involved in nutrient cycling. Nitrogen transformations are particularly sensitive because they depend on specialized microorganisms and enzymes. Reduced abundance of ammonia oxidizers and nitrite oxidizers under Cu stress limits nitrification processes, affecting nitrogen availability for plants [100].

The inhibition of nitrification observed in copper-contaminated soils reflects both direct toxicity and indirect effects caused by changes in microbial communities. The meta-analysis conducted by Elrys et al. [101] showed that copper concentrations above 150 mg kg^{-1} produced significant reductions in potential nitrification. Changes in enzyme activity, microbial biomass, and ammonia-oxidizing archaea contributed to decreased nitrogen transformation capacity. However, lower copper levels may temporarily increase nitrate availability due to changes in mineralization processes.

Heavy metal contamination can also modify nitrogen cycling pathways by altering microbial functional genes. In Cu and Cd contaminated paddy soils, increased abundance of *Nitrospira* contributed to enhanced nitrification and denitrification processes, whereas reduced nitrogen-fixing microorganisms indicated potential limitations in nitrogen inputs. These microbial shifts may lead to increased nitrogen losses and reduced long-term soil fertility [103].

4.5.3. Copper Mobility, Soil Properties, and Plant Interactions

Copper behavior in agricultural soils depends strongly on soil characteristics and management practices. High copper accumulation in vineyard soils demonstrates the long-term effect of repeated Cu inputs, particularly from agricultural treatments. The relationship between copper fractions and soil organic carbon indicates that organic matter plays an important role in controlling Cu availability. Spatial distribution patterns further demonstrate that cultivation practices influence copper accumulation within fields [104].

Soil acidity represents another important factor controlling copper toxicity. Acidic soils increase the mobility of metals, enhancing their interaction with plant roots and microorganisms. The presence of aluminum as a secondary stress factor can modify copper uptake by plants. In maize, Al co-stress reduced Cu adsorption and movement through changes in root surface charge and metabolic regulation, suggesting that plants employ multiple adaptation mechanisms in metal-contaminated environments [105].

The response of agricultural soils to copper pollution therefore depends on interactions among metal concentration, microbial adaptation, soil chemistry, and plant physiological processes. Copper contamination can reduce microbial diversity, disrupt nutrient cycling, promote resistance traits, and limit crop productivity, but resistant microbial populations and plant adaptation mechanisms may contribute to maintaining ecosystem functions under long-term exposure.

4.6. Plant Responses and Adaptation Mechanisms Under Copper Stress in Agricultural Systems

Copper contamination represents an important challenge for agricultural production because Cu is both essential and toxic depending on its concentration. The reviewed studies demonstrate that excessive Cu affects plant development through changes in growth, photosynthesis, nutrient balance, oxidative stress, and metal distribution within tissues.

Growth inhibition is one of the most common responses to Cu toxicity. Athar et al. [105] showed that Cu exposure reduced wheat growth and grain quality, while Houshmandfar [134] demonstrated similar reductions in safflower germination and seedling development. These effects are associated with disturbances in physiological processes and increased oxidative stress. Rob et al. [61] emphasized that Cu toxicity in rice affects photosynthesis, cellular metabolism, and plant defense pathways.

Plants have developed different strategies to cope with Cu stress. These include limiting uptake, storing metals in roots, binding Cu with organic compounds, and activating antioxidant mechanisms. Li et al. [64] showed that different plant species growing in the same contaminated environment displayed different Cu accumulation patterns, demonstrating species-specific responses. Napoli et al. [111] also classified several crops as Cu excluders because they restricted Cu movement into aboveground tissues.

The distribution of Cu between plant organs is important for determining agricultural risks. While roots frequently act as the primary storage tissue, some crops transport Cu into leaves, fruits, or grains. Alamer et al. [107] showed that Cu can accumulate in edible parts of tomato and eggplant, while He et al. [112] demonstrated differences among rice cultivars in grain Cu accumulation. These differences highlight the importance of selecting crops with low metal accumulation capacity in contaminated areas.

The risk of Cu transfer into the food chain is particularly important for crops grown near mining areas. Pu et al. [114] and Simonovic et al. [44] showed that crops cultivated in metal-affected regions may accumulate Cu and other metals, increasing potential risks for consumers. However, cultivar selection may help reduce these risks, as demonstrated by Qiu et al. [113], who identified pollution-safe vegetable cultivars with lower metal accumulation.

Some plants may also contribute to remediation of contaminated agricultural systems. Avkopashvili et al. [116], Rojas-Tapias et al. [117], and Wang et al. [63] demonstrated

that plant-based approaches combined with biological or soil amendments can reduce Cu stress and improve plant performance. Microbial inoculation and biochar application may increase plant tolerance while limiting metal uptake into edible tissues.

The use of plants for remediation must consider both accumulation ability and food safety. Noviardi et al. [115] showed that sweet potato can accumulate Cu and other metals efficiently, making it potentially useful for phytoremediation, but contaminated biomass should not enter the food chain. Similarly, Lajayer et al. [118] suggested that some aromatic plants may tolerate moderate Cu levels without compromising product quality.

Copper contamination therefore has multiple effects on agricultural plants, ranging from reduced productivity to altered metal distribution and potential human exposure. Sustainable management requires selecting appropriate plant species, using tolerant cultivars, applying biological approaches, and monitoring metal accumulation in edible tissues.

4.7. Interactions Between Copper and Other Heavy Metals in Contaminated Agricultural Soils

Copper contamination in agricultural soils represents a complex environmental problem because Cu accumulation is frequently linked with other toxic metals and multiple pollution sources. The reviewed studies demonstrate that agricultural soils exposed to industrial, mining, and agricultural activities commonly contain mixtures of metals rather than single-element contamination. This is important because combined metal exposure may influence soil properties, metal mobility, plant uptake, and potential risks to humans.

The distribution of metals in contaminated agricultural soils depends strongly on the pollution source. Industrial activities such as copper smelting can significantly increase Cu concentrations and alter its chemical fractions. Hu et al. [56] reported that Cu, Zn, Pb, and Cd in paddy soils near a copper smelting plant were strongly influenced by anthropogenic activities, while Ni, Co, and Cr were mainly associated with geological processes. The increased mobility of Cu compared with uncontaminated soils suggests that copper may become more environmentally available under certain soil conditions.

Copper contamination is frequently accompanied by other metals that may represent greater ecological or health risks. In Qatar agricultural soils, Cu concentrations were lower than several other metals, but the presence of As, Cr, Ni, and Zn above background values demonstrated the complexity of multi-metal pollution. Although Cu was not the dominant contaminant, its anthropogenic enrichment indicates that agricultural soils can accumulate copper from human activities [119]. Similarly, Ates et al. [120] showed that agricultural soils affected by industrial activity contained elevated concentrations of multiple metals, with contamination patterns reflecting both natural sources and human influence.

Mining activities are among the most important contributors to Cu contamination. The results from the Bookook Mine area showed that mine waste and drainage systems can transport metals into surrounding farmland, where they may enter agricultural soils and crops. Copper was detected together with Zn, Ni, As, Cd, and Pb, indicating that mining-related contamination affects several environmental compartments simultaneously [121]. Long-term persistence of contamination was also demonstrated in the Chenzhou mining area, where Cu and other metals remained in agricultural soils many years after the original pollution event. The continued presence of metals indicates that natural attenuation may be insufficient without effective remediation strategies [123].

The transfer of copper and associated metals from soil to plants represents a major concern for food safety. In wastewater-irrigated agricultural fields, Cu was among the metals exceeding soil quality limits, and vegetables accumulated heavy metals in edible tissues. The different accumulation patterns between plant species demonstrate that metal uptake depends on plant physiology, soil conditions, and metal bioavailability. Cao et al. [150]

found that certain vegetables accumulated high concentrations of metals and contributed to increased human health risks, particularly for children.

Metal toxicity in agricultural systems is not determined only by total metal concentration but also by chemical availability and interactions with plants and microorganisms. The study by Khan and Lee [125] demonstrated that beneficial endophytes can reduce the negative effects of Cu stress by improving plant growth, increasing nutrient uptake, and enhancing copper removal. The association between *Penicillium funiculosum* and soybean plants reduced oxidative stress and improved plant resistance, suggesting that biological methods may support remediation of Cu-contaminated soils.

The comparison between Cu and other heavy metals shows that copper pollution should be evaluated as part of a wider contamination system. Although some studies reported higher risks from As, Cd, Cr, or Ni, copper remains environmentally important because of its mobility, accumulation potential, and effects on plant growth at elevated concentrations. Effective management of Cu-polluted agricultural soils requires monitoring of multiple metals, identification of pollution sources, and the development of remediation approaches that reduce metal availability while maintaining agricultural productivity.

4.8. Advances, Limitations, and Future Perspectives in Copper Soil Remediation

Copper remediation aims to reduce bioavailability, remove Cu, or restore soil quality. Immobilization is suitable for reducing toxicity, whereas extraction is necessary when permanent removal is required.

Clay amendments effectively stabilize Cu. Bentonite decreased exchangeable Cu fractions [126]. Coal fly ash promoted zeolite formation, incorporating Cu into less available mineral phases [133]. Organic amendments also improve immobilization: rice husk biochar outperformed other amendments [151], sesame straw biochar reduced plant Cu uptake [129], and humic acid enhanced biochar performance [63]. Modified carbon materials [130], hydrogels [131], and cysteine-modified chitosan [64] offer additional stabilization options.

Extraction methods, including electrokinetic remediation and soil washing, can enhance Cu removal. EDTA and EDDS improved extraction efficiency [54,132], whereas humic substances offer potential alternatives with fewer environmental concerns [133]. Phytoremediation may benefit from natural amendments, as horse manure increased Cu uptake and biomass production [48]. However, chelator-assisted approaches can remain slow and inefficient [135].

Plant performance depends on species, soil conditions, and biological interactions. IAA and EDTA enhanced Cu accumulation in sunflower and maize [136], while mycorrhizal fungi improved Cu tolerance and binding [47,137]. AMF reduced Cu transfer to soybean shoots [142], and beneficial bacteria enhanced plant resistance [60]. Promising candidates include *Brassica nigra* and *B. juncea* [129], kenaf [141], and jute varieties C-3 and HT [66]. Nitrogen and phosphorus increased Indian mustard biomass and total Cu removal [61]. Myrtle [60], halophytes [140], and *Leucaena leucocephala* [146] may support stabilization and ecosystem recovery. Bamboo–*Sedum* intercropping enhanced microbial diversity and metal removal [145], while biostimulation and bioventing supported Cu removal from contaminated soils [152].

Nevertheless, phytoextraction remains limited by low Cu availability and strong soil retention. Metal-accumulating plants often remove insufficient Cu [145]; lupin improved soil biological activity but extracted little Cu [146]. Iron oxide nanoparticles did not significantly reduce Cu accumulation or toxicity in sunflower [147], and pepper showed limited Cu bioaccumulation [153]. Copper-resistant Rhizobiales may contribute to natural attenuation [145].

No single technique suits all contaminated soils. Integrated approaches combining immobilization, extraction, plants, and beneficial microorganisms may improve remediation, provided that treatment selection considers soil properties, crop safety, and long-term environmental effects.

4.9. Research Gaps, Future Directions, and Management Needs

4.9.1. Research Gaps

Despite the rapid growth in publications addressing copper (Cu) pollution in agricultural soils, several important knowledge gaps remain. Most available studies are geographically concentrated in a limited number of countries, particularly China, while large agricultural regions in Africa, South America, Eastern Europe, and Southeast Asia remain poorly investigated. Consequently, the global distribution and severity of Cu contamination are still incompletely understood.

Another major limitation is the predominance of short-term laboratory and greenhouse experiments. Although these studies provide valuable mechanistic insights, they often fail to represent the complexity of field conditions where soil properties, climate, cropping systems, and agricultural management interact over long periods. Long-term field experiments evaluating Cu accumulation, mobility, and ecological recovery remain scarce.

Current research also focuses primarily on total Cu concentrations, whereas relatively few studies investigate Cu speciation, bioavailability, and transformation processes controlling its environmental behavior. Because toxicity depends largely on the bioavailable fraction rather than total Cu content, future studies should prioritize chemical speciation and dynamic changes in Cu fractions under different environmental conditions.

Although numerous studies have documented the effects of Cu on crop growth and soil microorganisms, limited information is available regarding the long-term impacts on soil ecosystem services, nutrient cycling, carbon sequestration, biodiversity, and resilience of agricultural ecosystems. Similarly, interactions between Cu contamination and climate change factors, including drought, elevated temperature, flooding, and changing precipitation patterns, remain insufficiently explored.

Another significant research gap concerns the combined occurrence of Cu with other potentially toxic elements. Agricultural soils are rarely contaminated by Cu alone; instead, they are commonly affected by mixtures of Cd, Pb, Zn, As, Ni, and Cr. However, relatively few studies investigate synergistic or antagonistic interactions among multiple contaminants and their combined effects on soil health, crop productivity, and human health.

Advances in molecular biology and environmental genomics have improved understanding of microbial responses to Cu stress, yet the mechanisms governing microbial adaptation, antibiotic resistance gene dissemination, and microbiome recovery after remediation remain poorly understood. More studies integrating metagenomics, transcriptomics, metabolomics, and soil biogeochemistry are required.

Finally, although numerous remediation technologies have been proposed, direct comparisons among different remediation strategies under similar field conditions are limited. Information regarding their long-term effectiveness, economic feasibility, environmental sustainability, and scalability for practical agricultural applications is still insufficient.

4.9.2. Future Research Directions

Future research should move toward integrated and multidisciplinary approaches combining soil science, agronomy, environmental chemistry, microbiology, remote sensing, ecology, and environmental engineering.

Priority should be given to establishing long-term monitoring networks capable of assessing temporal changes in Cu accumulation, bioavailability, and ecological risks across

different agricultural systems. Harmonized international monitoring protocols would improve data comparability and facilitate global risk assessment.

Greater emphasis should also be placed on developing rapid, non-destructive monitoring technologies. The integration of hyperspectral imaging, portable X-ray fluorescence (pXRF), unmanned aerial vehicles (UAVs), Internet of Things (IoT) sensors, artificial intelligence, and machine-learning algorithms offers considerable potential for precision assessment of Cu contamination at both field and regional scales.

Future investigations should also improve understanding of Cu speciation under varying soil conditions, including changes in pH, organic matter, redox potential, and microbial activity. Such knowledge is essential for accurately predicting Cu mobility, plant uptake, and environmental risks.

Additional research is needed to identify crop cultivars with low Cu accumulation capacity while maintaining high productivity. Simultaneously, greater attention should be devoted to beneficial microorganisms, including plant growth-promoting rhizobacteria, arbuscular mycorrhizal fungi, and endophytic microorganisms that enhance plant tolerance and reduce Cu bioavailability.

Novel remediation technologies should continue to be developed, including engineered biochar, nanomaterials, functionalized biosorbents, microbial-assisted remediation, phytoremediation, electrokinetic remediation, and integrated remediation systems combining physical, chemical, and biological approaches. Future studies should evaluate not only remediation efficiency but also environmental safety, economic viability, carbon footprint, and long-term sustainability.

Research should also expand toward food safety and public health by investigating Cu transfer through soil–plant–animal–human pathways, dietary exposure, cumulative health risks, and socio-economic impacts of contaminated agricultural land.

4.9.3. Management Actions Needed

Effective management of Cu pollution requires an integrated strategy combining prevention, monitoring, remediation, and sustainable agricultural management.

Preventive measures should focus on reducing Cu inputs into agricultural soils by optimizing fertilizer and pesticide application, promoting integrated pest management, and encouraging alternatives to copper-based fungicides where feasible. Particular attention should be given to vineyards, orchards, and intensive horticultural systems, where repeated Cu applications often result in long-term accumulation.

Regular soil-monitoring programs should be implemented to evaluate total and bioavailable Cu concentrations using standardized analytical methods. Risk assessment should include not only soil contamination levels but also crop uptake, groundwater vulnerability, ecological impacts, and potential human exposure.

Agricultural management practices should promote soil conditions that minimize Cu mobility and bioavailability. Maintaining adequate soil organic matter, avoiding excessive soil acidification, improving soil structure, and applying suitable organic or mineral amendments can substantially reduce Cu toxicity.

Where contamination exceeds acceptable thresholds, site-specific remediation strategies should be selected according to contamination level, soil characteristics, land use, and economic considerations. Immobilization using biochar, compost, clay minerals, or other amendments may be appropriate for moderately contaminated soils, whereas heavily contaminated sites may require integrated remediation combining phytoremediation, microbial technologies, and engineering approaches.

Policy development should strengthen regulatory frameworks governing Cu use in agriculture, establish harmonized soil quality standards, and promote sustainable man-

agement through financial incentives and extension services. International collaboration is also needed to develop common monitoring protocols, share databases, and support technology transfer.

Finally, successful management depends on increasing awareness among farmers, land managers, policymakers, and the public regarding the risks associated with excessive Cu accumulation and the benefits of sustainable soil management. Education, technical training, and knowledge transfer programs should therefore become integral components of national soil protection strategies.

Overall, future progress in managing copper pollution will require the integration of advanced scientific knowledge with practical agricultural management, environmental policy, and long-term monitoring to ensure soil health, food security, ecosystem sustainability, and protection of human health.

5. Conclusions

Copper is an essential micronutrient for plants, but its excessive accumulation in agricultural soils represents an important environmental and agricultural concern. The thematic synthesis indicates that Cu contamination is associated with multiple anthropogenic sources, including mining and smelting activities, wastewater irrigation, intensive livestock production, and the prolonged application of copper-based fungicides and Cu-enriched pig and poultry manure, particularly in vineyards and orchards. Because Cu does not degrade, its persistence and accumulation in soils can increase the risk of adverse effects on soil quality, crop productivity, ecosystem functioning, and food safety. The magnitude of these effects depends on soil properties, Cu speciation and bioavailability, contamination levels, and land-management practices.

The reviewed evidence indicates that elevated Cu concentrations can alter soil physicochemical properties, affect microbial diversity and community composition, and interfere with nutrient cycling and the activity of microorganisms involved in biogeochemical processes. In plants, excessive Cu exposure can induce oxidative stress, impair photosynthetic activity, and restrict growth and productivity. Cu accumulation in edible plant tissues may also create potential risks to food safety and human health. However, the severity of these effects varies among soil types, crop species, exposure conditions, and environmental settings; therefore, findings from individual experiments should not be directly extrapolated to all agricultural systems without appropriate field validation and site-specific risk assessment.

The bibliometric analysis provides a complementary perspective on the development and structure of research on Cu pollution in agricultural soils. The publication trends indicate growing scientific interest, particularly in recent years, while the geographical distribution of research highlights the contributions of countries with substantial agricultural and industrial activity. Emerging research topics include advanced monitoring technologies, machine-learning applications, microbial ecology, and innovative remediation approaches. These findings identify prominent research themes and potential directions for future investigation, but publication counts and keyword patterns do not, by themselves, establish the effectiveness of remediation technologies or the magnitude of environmental risks. The bibliometric results should therefore be interpreted as indicators of research activity and thematic development rather than direct evidence of environmental outcomes.

Nevertheless, the presence of elevated total Cu concentrations should not be interpreted as direct evidence of a specific level of ecological damage or human-health risk. Such conclusions require consideration of Cu availability, soil properties, biological responses, crop accumulation, relevant exposure pathways, and the duration and intensity of exposure. In agricultural systems affected by multiple metals, the contribution of Cu should be

evaluated separately where the available evidence permits, and site-specific risk estimates should be distinguished from general conclusions about Cu contamination.

The thematic synthesis identifies several approaches for managing Cu-contaminated agricultural soils, including phytoremediation, microbial-assisted remediation, biochar application, soil amendments, immobilization techniques, electrokinetic remediation, and engineered adsorbent materials. Their effectiveness depends on the contamination level, soil characteristics, Cu speciation, land use, climatic conditions, implementation costs, and intended remediation objectives. An important distinction must be made between Cu removal from soil, reduction of Cu mobility and bioavailability, and restoration of soil biological and ecological functions. Immobilization and stabilization may reduce exposure and ecological risks without substantially decreasing total soil Cu concentrations, whereas removal-oriented technologies aim to extract Cu from the contaminated matrix but may involve greater costs, technical constraints, or disturbance of soil properties. Consequently, no single remediation strategy can be considered universally superior. The selection of an appropriate intervention should be based on site-specific conditions, the intended endpoint, and evidence of its effectiveness and potential unintended effects.

Several knowledge gaps limit the translation of current findings into broadly applicable management recommendations. These include the limited availability of long-term field validation for many remediation technologies, incomplete understanding of Cu speciation and bioavailability under changing environmental conditions, interactions between Cu and other contaminants, and the potential effects of climate change on Cu mobility and toxicity. Further research is also needed to assess the persistence of remediation benefits, the recovery of soil microbial communities and ecosystem functions, and the economic and environmental feasibility of scaling up promising technologies. Comparisons using standardized indicators of Cu removal, risk reduction, and soil-function recovery would improve the evaluation of different interventions and support more consistent decision-making.

Preventing further Cu accumulation should remain a priority through the rational use of copper-containing fertilizers and fungicides, appropriate management of wastewater and livestock-derived inputs, and regular monitoring of soil Cu concentrations and bioavailability. Where contamination has occurred, remediation decisions should be guided by site-specific risk assessments and clearly defined objectives, distinguishing contaminant removal from immobilization, exposure reduction, and ecological restoration. Integrating preventive management, monitoring, and appropriately selected remediation measures can help protect agricultural productivity, soil health, and food safety. Continued interdisciplinary research and international collaboration are needed to strengthen field-based evidence, develop cost-effective and environmentally compatible interventions, and support the long-term sustainability of agricultural ecosystems.

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