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Plant uptake of environmental contaminants when sewage sludge is used in agriculture

A systematic review protocol

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Plant uptake of environmental contaminants when sewage sludge is used in agriculture. A systematic review protocol

This systematic review protocol has been developed by Formas in collaboration with external subject experts.

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Abstract

The use of sewage sludge in agriculture has gained attention due to its potential benefits and risks. Sewage sludge, a byproduct of wastewater treatment, is rich in nutrients and organic matter, making it a valuable soil amendment. However, it also contains various environmental contaminants, such as heavy metals and organic contaminants, which can accumulate in soil and crops. Understanding the extent of pollutant uptake by plants and concentration in soil is central for developing safe and sustainable agricultural practices.

This systematic review aims to quantify the concentration of various environmental pollutants in soils and crops when sewage sludge (regularly or occasionally) is used in agriculture. By assessing the accumulation and uptake of contaminants by different crops, the review also seeks to identify factors influencing these effects, such as sludge properties, application rates and interval, soil type, crop type, and pollutant concentration in the sludge.

To conduct the review, we will systematically search for literature using bibliographic databases, search engines, and relevant websites. References will be screened for relevance based on predefined eligibility criteria. The screening process will occur in two stages: initially by title and abstract, followed by full-text screening. The full-text screening will be conducted independently by two reviewers with blind decisions. Each relevant study will undergo critical appraisal using predefined criteria. The review will include a narrative synthesis and when possible quantitative syntheses through meta-analyses. The results will be discussed in relation to the positive aspects of using sewage sludge in agriculture.

This systematic review supports Sweden's environmental quality objective of achieving a non-toxic environment. Key stakeholders, including the Swedish Environmental Protection Agency and the Swedish Board of Agriculture, are expected to utilize the findings to inform policy and practice.

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Background

In the search for sustainable ways to recover nutrients and reuse resources, sewage sludge presents both opportunities and challenges. On the one hand, it is a nutrient-rich byproduct of wastewater treatment, offering considerable potential to enhance soil fertility and reduce reliance on synthetic fertilizers. On the other, it contains a complex and evolving mixture of environmental contaminants, some of which pose documented risks to ecosystems and human health. Using sewage sludge in agriculture is not a new practice and has been debated for several years. Also, the topic was summarized in an official government report in 2020 [1].

Wastewater treatment and derivation of sewage sludge

Wastewater treatment aims to remove oxygen-consuming organic substances and, depending on the receiving body, plant size, and other factors and regulations, also nutrients (Nitrogen and Phosphorus). Treatment levels (and treatment processes) are often categorized as primary, secondary, and tertiary. Primary and secondary treatment focus on the removal of organic substances, while tertiary treatment normally refers to the removal of phosphorus and nitrogen. The definitions are not entirely consistent, and alternative phrasings appear in the literature that may better describe the actual treatment processes. Enhanced secondary treatment is sometimes used to refer to nitrogen and phosphorus removal if the secondary treatment is configured for removal of nutrients [2]. In the revised European Urban Wastewater Treatment Directive [3], requirements are also set for quaternary treatment, which involves the removal of organic microcontaminants, such as pharmaceutical residues, hormones, cosmetics, and biocides. This division, into primary, secondary, tertiary, and quaternary treatment, also reflects a historical development with increasingly stringent effluent requirements, a development that has influenced both sludge volumes and sludge characteristics.

All treatment processes generate residual products. According to the Swedish glossary for water and wastewater treatment issued by Terminologicentrum [4], wastewater sludge is defined as "sludge obtained as waste during the treatment of wastewater." In the same glossary, sludge is defined as "particles suspended in liquid at high concentration." Sometimes a distinction is made between primary and secondary sludge (waste activated sludge) and occasionally also between biological sludge and chemical sludge to indicate the origin of the sludge, either from biological treatment (which may be secondary or tertiary) or from chemical treatment, which in turn can be integrated with other treatment steps thus creating either a separate or a mixed stream of sludge depending upon configuration.

Sludge treatment primarily aims to reduce water content through thickening (by means of gravity thickeners or mechanical thickeners) and dewatering (by means of centrifuges, filters and presses), often with the addition of metal salts and polymers to ease handling and reduce resource consumption in subsequent steps. Conventional sludge treatment also includes stabilization to stop biological activity and sometimes further hygienization to reduce pathogen levels. Sludge can be stabilized by several different methods (anaerobic or aerobic stabilization, thermal oxidation lime addition, composting etc.), with anaerobic digestion being common at midsize and large

wastewater treatment plants in Sweden (larger than 20 000 – 30 000 population equivalents). Many smaller wastewater treatment plants and single house plants are transporting their sludge to plants with anaerobic digestion. Approximately 90% of all the sludge in Sweden is therefore anaerobically digested. Anaerobic digestion not only stabilizes the sludge but also enables biogas production for generation of electricity, heat or further upgrading to biomethane for vehicle fuel. After treatment, sewage sludge is in some countries referred to as biosolids. In recent years, various methods for sludge treatment have emerged, for example pyrolysis for production of biochar as a means to reduce volumes, degrade contaminants, and recover phosphorus.

Producing biochar from sludge can offer numerous benefits, where the sludge volume is reduced by 80% and pathogenic agents and hazardous compounds from sewage sludge are removed or reduced. At the same time, the process also implies loss of nitrogen and other volatile nutrients and the phosphorus availability in the product is questionable. Using biochar on arable land can result in improved soil structure, increased water retention, enhanced microbial habitat, and nutrient retention in soil [5]. However, the effects vary depending on soil type and climatic conditions and further evaluation under Swedish conditions is needed. Issues concerning practical usage of biochar on farm level also need solutions. Under the current EU Fertilising Products Regulation (FPR 2019/1009), sewage sludge is explicitly excluded from eligible feedstocks for pyrolysis and gasification materials (CMC 14), meaning sludge-derived biochar cannot be marketed as an EU fertilising product. Several EU countries (Sweden, Denmark, Finland, Czech Republic) have national schemes that permit sludge-derived biochar under tightly controlled pyrolysis conditions.

Another way of recirculating nutrients from sewage sludge is incineration followed by extraction of phosphorus and other nutrients from the ash. This method allows production of products similar to other mineral fertilizers, but with the drawback that organic substances and nitrogen are lost in the process. The fertilizers derived from the ash can be used in Swedish agriculture if it fulfills the requirements set by EU and Swedish regulations (EU 2019/1009). Since the properties and contents of this type of fertilizer products are greatly differing from the original sewage sludge, they are not included in this review.

New definitions, albeit somewhat arbitrary and sometimes fluid, strive toward a perspective of taking *waste* out of wastewater. In this context wastewater treatment plants are viewed as resource recovery facilities and sludge is not necessarily considered as waste. Waste or not waste, wastewater sludge can originate from various treatment steps and be processed in different ways affecting the content of nutrients, organic matter, and the presence of other substances and components originating from the wastewater.

Common contaminant groups found in sewage sludge

Sewage sludge is a complex matrix that can contain a wide range of contaminants, reflecting the diversity of different kinds of sewage water connected to WWTPs. Commonly observed contaminants include heavy metals, organic contaminants, pharmaceutical residues, and pathogenic microorganisms. The composition of incoming wastewater, particularly from industrial sites, hospitals and densely populated urban areas, has a significant impact on the types and concentrations of contaminants present in the resulting sludge. Seasonal dynamics can also play a role.

The sorption behavior of these components is largely governed by their physicochemical properties. Hydrophobic compounds tend to bind more readily to the organic matter in sludge. However, compounds with polar functional groups (e.g. $–NH_2$, –COOH) may also adsorb via electrostatic interactions with the negatively charged sludge surface. Factors such as suspended solid size, carbon content, and cation exchange capacity further influence sorption dynamics, although clear mechanistic trends are not fully established.

Inorganic contaminants such as cadmium (Cd), copper (Cu), nickel (Ni), lead (Pb), zinc (Zn), mercury (Hg), and chromium (Cr) are among the most well-studied and are regulated under the EU Sewage Sludge Directive (86/278/EEC). Several EU Member States have introduced more stringent national regulations for these substances.

Organic contaminants found in sludge include both regulated substances and emerging contaminants. Regulated compounds often include nonylphenols and nonylphenol ethoxylates (NPEs), alkylbenzene sulfonates (LAS), adsorbable organic halides (AOX), di(2-ethylhexyl) phthalate (DEHP), polycyclic aromatic- hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), PFOS, PFOA, PFHxS and dioxins (PCDD/Fs).

In addition, other organic contaminants, including degradation products, have been identified in several studies [6-8]. Priority lists from evaluations of persistence, bioaccumulation potential, mobility and toxicity indicate that several contaminant groups found in sludge and biosolids are of concern. Examples are per- and polyfluoroalkyl substances (PFAS), polychlorinated alkanes (PCAs), polychlorinated naphthalenes (PCNs), organotins, polybrominated diphenyl ethers (PBDEs), triclosan (TCS), triclocarban (TCC), benzothiazoles, synthetic musks, phenols quaternary ammonium compounds (QACs), , steroids and hormones, phthalate acid esters (PAEs), and polydimethylsiloxanes (PDMSs) [9]. The large group PFAS are of particular concern due to their extreme persistence in the environment and potential for bioaccumulation. Although the production and use of PFAS substances like PFOS and PFOA have been restricted for several years, not only in the EU but also globally via the UN Stockholm Convention, they are still frequently detected in sludge. Due to the complexity of the sludge matrix and the vast number of chemicals registered for use in the EU (over 140,000), comprehensive chemical identification is not feasible. Both targeted and non-targeted analytical methods are used, but each has limitations. Bioassays are increasingly used to evaluate the overall toxicity of complex mixtures rather than focusing on individual substances [10].

Use of sewage sludge in Sweden

Even though sewage sludge can contain several unwanted components, it also contains relatively large amounts of macro- and micronutrients and organic matter, making it a valuable source for crop production in agriculture. The average concentration of nitrogen and phosphorus in Swedish sludge were 4-5% and 2.5-3%, respectively during the period 2010-2022 [11]. In 2022, about 50% of all sewage sludge produced in Sweden was used in agriculture which corresponds to approximately 1,5 and 8,3 % of total input of nitrogen and phosphorus, respectively (SCB, 2022) [12]. Besides nitrogen and phosphorus, sludge also contributes to the addition of micronutrients and organic matter to arable soils.

All usage of sewage sludge on arable land is regulated by EU and Swedish law [13-15]. Firstly, there is a maximum amount of phosphorus and nitrogen that can be applied to arable land as sewage sludge, which in practice implies an average addition not exceeding 22 kg of phosphorus per hectare and year [13]. Secondly, there are regulations that demand treatment of the sludge before use, prescribe maximum concentrations of heavy metals in soil and sludge, as well as include restrictions for application on land used for grazing and vegetable production [14]. In addition to these directives, the buyers of agricultural products have set their own restrictions that further limit or prohibit the use of sludge on arable land. The WWTPs have, through the branch organization the Swedish Water and Wastewater Association (Svenskt Vatten), in cooperation with LRF, the Federation of Farmers and LI, the Swedish food industry association a common certificate system called Revaq. The aim of Revaq is to improve the quality of incoming wastewater and thereby of the sludge and creating acceptance among the farmers and the food industry [16]. Most buyers of agricultural products require that the sludge is produced within Revaq, and due to this, about 80% of sludge used in agriculture is approved through this certificate. Even so, there are further limitations set by the buyers. Furthermore, application of sewage sludge to organic farms is currently prohibited in the European legislation for organic farming [17, 18]. These regulations and policies aim to make the most of the valuable nutrients and organic matter in sludge, while also protecting food safety, soil health, and the environment. But even after decades of research, we still lack clear answers about potential risks for some groups of contaminants, especially how contaminants from sludge behave in different soils and crops. There is also uncertainty due to differences in study methods, variations in sludge content, and lack of long-term data.

This tension highlights a critical gap in our current knowledge. Although previous reviews have examined specific contaminants or pathways, there is still no comprehensive and methodologically rigorous synthesis that captures the full range of contaminants found in sewage sludge, such as heavy metals, organic compounds, pharmaceuticals, and microplastics, and assesses their behavior in soil–crop systems under real-world agricultural conditions. In the absence of such review, decisions and practical applications risk being based on incomplete or outdated evidence.

The debate around sludge reuse goes beyond scientific uncertainty and reflects deeper value-based tensions among stakeholders. Advocates of the circular economy emphasize resource efficiency, while environmental groups call for greater precaution. Farmers value sludge as a low-cost fertilizer and as a way to increase organic matter in soil, yet food producers remain cautious about potential risks to consumers. Decision makers must meet goals of sustainable waste management while at the same time limiting chemical exposure. These different priorities highlight the need for a systematic, transparent, and unbiased review. One that not only clarifies current knowledge but also sheds some light on remaining uncertainties that may influence future decisions.

This review aims to meet that need by systematically identifying, evaluating, and synthesizing research on how contaminants from sewage sludge degrade and accumulate in soils and are taken up by crops. Through this extensive evidence base, we aim to support more informed and transparent decision-making. The findings will contribute directly to the European Commission's vision to a competitive circular economy and Sweden's goal of achieving a non-toxic environment and contribute to a more evidence-driven discussion about the role of sludge in sustainable agriculture.

We recognize that the review does not cover all aspects of the use of sewage sludge in agriculture, excluding the benefits of sewage sludge in comparison to conventional fertilizers, the possible leaching of different contaminants to the surrounding environment and ground water as well as the impact on organisms in the soil. It also does not cover the use of sewage sludge in other locations or for other purposes such as fertilizers in the forest or for landfills. The scope of the review was set to be relevant to the risk associated with human consumption when sewage sludge is used in agriculture. This boundary was established because this issue is significant for the acceptance of the use of sewage sludge in society. Although not all aspects of sewage sludge use will be systematically reviewed, the implication of the result from the review on the above-mentioned aspects will be highlighted in the discussion.

Published and ongoing evidence synthesis

To find out the need for a systematic review on this topic a search for systematic reviews or other types of evidence synthesis reports was made. A search was carried out in Web of science[1]. In addition, The CEE Database of Evidence Reviews [19] and PROCEED [20], a global database of prospectively registered evidence reviews and syntheses in the environmental sector, were searched using the terms sludge and biosolids.

In total, four published reports were found with relevance to the topic.

- Recovery of plant nutrients from human excreta and domestic wastewater for reuse in agriculture: a systematic map and evidence platform [21].
- Potential for Increased Human Foodborne Exposure to PCDD/F When Recycling Sewage Sludge on Agricultural Land [22].
- Review of Sewage Sludge as a Soil Amendment in Relation to Current International Guidelines: A Heavy Metal Perspective [23].
- Personal care products in soil-plant and hydroponic systems: Uptake, translocation, and accumulation [24].

One of the identified reports is an evidence map with a different aim than a systematic review. The remaining 3 reports include a systematic search for published literature on a part of the topic covered in this protocol. The reports do not cover the entire topic and have methodological limitations when assessed for objectivity, comprehensiveness and transparency of the synthesis using the Collaboration for Environmental Evidence Synthesis Assessment Tool (CEESAT) tool[2] [25]. We therefore conclude that the current systematic review is important and non-redundant. The studies included in the identified reports will be screened for relevance to the current project.

[1] Search string: ((TS=((agricultur* OR agroecosystem* OR crop* OR cultivat* OR farm*))) AND TS=(sludge*)) AND TS=(review)).
[2] Due to several different reasons, such as not having a protocol, not using a comprehensive search strategy, not reporting eligibility decisions transparently and not including critical appraisal of the included studies.

Objectives

The primary objective of the review is to quantify concentration of different environmental contaminants in soil and crops when sewage sludge (regularly or occasionally) is used in agriculture.

In quantifying the concentration of different environmental contaminants that are accumulated in soils and crops, the review also aims at identifying factors that influence these processes (see section on potential effect modifiers/reasons for heterogeneity).

Review questions

The main questions of the review are:

Based on data from empirical studies: When sewage sludge is used in agriculture:

1. To what extent are various environmental contaminants taken up by plants?
2. To what extent are various environmental contaminants accumulated in soil?
3. Is uptake in plants and accumulation in soil affected by different factors, such as:
    a. rate and interval of sludge application
    b. soil properties
    c. type of crop
    d. part of the crop
    e. concentrations of the contaminants in the sludge
    f. agriculture practices?

Definitions of the review question components

To be included in the review the studies must meet the criteria outlined in Table 1. These criteria define the fundamental elements of the review question, i.e., eligible study population, intervention, comparator, and outcome (PICO).

Table 1. Eligibility criteria.

Element	Definition
Population	Agricultural soil, including greenhouse and raised beds.
Intervention	Sewage sludge/biosolids, untreated and treated (composted or digestated), biochar produced from sewage sludge. Used alone or in combination with other fertilizers
Control	No sewage sludge (with or without other fertilizers) For studies on biochar, use of sewage sludge will also be accepted as a control option.

Outcome	Uptake of contaminants in edible plants (for human or animal consumption) and concentration in the soil where the plants were grown. Examples are pharmaceuticals, personal care products, industrial chemicals, pesticides, and degradation products, as well as microplastic particles, antibiotic- resistance genes, and contaminants of emerging concern. **Examples of contaminants are:** *Inorganic contaminants:* • heavy metals cadmium (Cd), led (Pb), mercury (Hg), tin (Tn), copper (Cu), chromium (Cr), nickel (Ni), zinc (Zn) • arsenic (As). *Organic contaminants:* • per- and polyfluoroalkyl substances (PFAS) • polychlorinated biphenyls (PCBs) • polyaromatic hydrocarbons (PAHs) • phenols • linear alkylbenzenes and sulfonates • polychlorinated dioxins and furans (PCDD/Fs) • brominated flame retardants (BFRs) • organophosphates • benzothiazoles • siloxanes • organotines • steroids / hormones • analgesics and anti-inflammatory drugs.
Study design	Only controlled studies will be included
Geographic area	No limitation
Publication year	No limitation
Language	English, Swedish, Norwegian, Danish, Finnish, German and French.

Study selection criteria

In addition to the eligibility criteria defined by above, the following inclusion and exclusion criteria will also be applied.

Inclusion criteria

- Agriculture soil in the field, greenhouses, or raised beds are included.
- Conference papers that constitute complete reports are included.
- Reports and book chapters are included.

Exclusion criteria

- Studies only measuring accumulation of contaminants in soil and not reporting any data on plant uptake will be excluded.
- Industrial waste is excluded.
- The use of wastewater for irrigation of agriculture soil as an intervention is excluded.
- Rice is excluded.
- The transfer of pathogens from sludge is excluded.
- The impact on soil organisms is excluded.
- Studies aimed at soil remediation are excluded.
- Dissertations, books and theses are excluded.
- Conference papers that are only abstracts are excluded.
- Nutritional effects of sludge, uptake of substances that are not considered to have any potential harmful effect at higher concentrations, such as phosphorus and nitrogen, are excluded.

Potential effect modifiers and reasons for heterogeneity

Parameters that may explain heterogeneity among study results are mainly related to soil properties, type of crops, agriculture practices differences in quality of the sludge, and application rate and interval of the sludge. The factors in Table 2 will be explored as possible effect modifiers if the results demonstrate a large degree of heterogeneity.

Table 2. Potential effect modifiers

Effect modifier	Parameters to be recorded
Soil properties	Soil type, soil texture, C/N ratio, pH, moisture class.
Sludge application	Rates and intervals.
Properties of contaminants	Hydrophobicity, water solubility, water-soil partitioning.
Crop properties	Type and part of crops.
Climate	Climate zone, mean annual temperature, mean annual, precipitation.

Contaminants in the sludge	Concentration of the contaminants in the sludge. If this is not reported, country or wastewater treatment process could be used as a proxy for this modifier.
Time since intervention	Time between intervention and measurement.
Year of study	Year the study was conducted.
Cultivation setting	Field or greenhouse.
Agriculture practices	Use of pesticides, Use of plastic film, harvest level.

Stakeholder engagement and relevance for Swedish conditions

A non-toxic environment is one of 16 environmental quality objectives in the Swedish environmental objectives system, adopted by the Swedish parliament in 1999 [26]. The responsible agency for this environmental quality objective, the Swedish Chemicals Agency, is one of the stakeholders of the planned systematic review. The Swedish Environmental Protection Agency and The Swedish Board of Agriculture are other key stakeholders.

In preparation for this systematic review protocol, representatives from the key stakeholders as well as the The National Food Agency, the Swedish Water and Wastewater Association, the Federation of Swedish Farmers (LRF), Lantmännen, Hushållningssällskapet and the Swedish Society for Nature Conservation (Naturskyddsföreningen) were invited to give input on the review question criteria and the inclusion and exclusion criteria.

The following organizations also commented on the draft of this protocol: The Swedish Environmental Protection Agency, The Swedish Board of Agriculture, the Swedish Water and Wastewater Association, the Federation of Swedish Farmers (LRF) and Hushållningssällskapet.

Methods

Literature search

Search for scientific literature will be conducted using Web of Science Core Collection, Scopus, CAB Abstracts, ProQuest Agricultural Science Collection, PubMed and Overton. The databases are accessed through Formas Institutional subscription.

Searches for grey literature will be conducted using BASE (Bielefeld Academic Search Engine), SwePub, Open Alex, and Google Scholar. These archives and search engines may also contain scientific literature. The search in Google Scholar will be performed in Publish or Perish. The first 200 search results for each search string will be screened for relevance.

We will also search for literature on relevant websites and by using stakeholder contacts. Search languages will be English in the scientific literature databases and English or Swedish in the searches for grey literature depending on the source. In three of the bibliographic databases: CAB, ProQuest, and Overton, a language filter is applied to the retrieved articles. Articles in English, French, Swedish, Danish, Finnish and Norwegian are retained (for the rest of the databases, non-included language will be removed in EndNote). Search strings (combinations of terms using Boolean characters) and further details for each source are shown in Additional file 1. Our search strategies and terms are adapted to align with the unique characteristics of each platform.

Additional searches will be made in bibliographies of relevant review articles identified in the screening process. The comprehensiveness of the searches will be assessed by comparing the search results with a list of relevant articles that were compiled before any searches were conducted (see Additional file 1). Contributions to this list of benchmark articles were provided by the authors of this protocol and stakeholders consulted at an early planning stage of the review.

An updated search will be considered within one year.

Screening strategy

The records found in the searches will be imported to EndNote, deduplicated using EndNote and DedupEndNote, and further exported to Rayyan for screening [27]. The literature screening will be a two-stage process: in the first stage based on titles and abstracts and in the second stage based on full text. Initially at the first stage, a subset of 100 titles and abstracts will be screened by all reviewers. Disagreements will be resolved and if necessary, the eligibility criteria will be clarified. Following this the references will be single screened based upon title and abstract. The reviewer will have three options during the screening process: (1) include, (2) exclude, or (3) maybe include. Option 2 (exclusion) will be applied only if it is completely obvious that the topic is out of scope. Articles coded with option 3 will be screened by a second reviewer. Any record listed as included by either reviewer will be brought forward to the second stage.

In the second stage, all articles included in the first step will be screened in full text. This will be done by two reviewers, with blinded decisions. At stage two, disagreements will initially be discussed and resolved by the two reviewers. If needed, all reviewers will be involved in resolving doubtful cases. During the screening process of the full text, the records will be coded with one of the codes in Table 3. Even though several reasons for excluding an item may apply, each item will be coded with only one reason to exclude. To avoid potential conflicts of interest, members of the review team will not participate in decisions regarding the inclusion or exclusion of studies in which they themselves were authors. The results of the screening process will be shown in a PRISMA flow diagram [28, 29].

Table 3. Coding options at stage 2 (full text).

	INCLUDE
	EXCLUDE on Population
	EXCLUDE on Intervention
Codes for full text screening	EXCLUDE on Comparator

	EXCLUDE on Outcome
	EXCLUDE on Study type
	EXCLUDE on Publication Format
	EXCLUDE on Language
	EXCLUDE other reason

Data extraction

A pre-designed data extraction form will be developed in an Excel spread sheet and piloted before use to ensure it captures all necessary information. The data extraction form will capture relevant study information, including, but not limited to:

- study identification details (author, year, country)
- soil and crop characteristics
- sludge characteristics
- outcome measures and results.

Data (results) and meta-data will be extracted from included studies by one reviewer possibly using an AI tool such as Elicit for assistance [30]. To test the repeatability of the process, and to assess the risk of mistakes in the data and meta-data extraction, a second reviewer will independently extract data and meta-data from a subset of included articles. If an AI tool is used for assistance all extracted data will be checked by a second reviewer. Any disagreements will be resolved through discussions within the review team. Any doubts during data extraction will be discussed and resolved among all reviewers. Data (results) will be extracted for contaminants which have been studied in at least three different studies, otherwise only metadata will be extracted and summarized. All extracted data will be available in an additional file to the final report.

The extracted data will be recorded as reported in the included studies and if necessary standardized in the synthesis stage. If repeated measurements have been carried out, data for the most relevant reported time points will be recorded.

In cases where outcome data are only reported in graphic figures, we will use WebPlotDigitizer to extract data [31].

If an article contains missing data or unclear information, we will only reach out to the corresponding author for additional details in exceptional cases where that information might make a substantial contribution to the overall report.

Study validity assessment, critical appraisal

Critical appraisal of relevant studies will include an assessment of internal and external validity.

Internal validity

Each study will be assessed on the risk of bias. The purpose of the study validity assessment is to reduce the risk that the conclusions of the review are misleading. We aim to assess each study's internal validity from a set of criteria (such as confounding bias and performance bias), based on the CEE Critical appraisal tool, version 0.3 [32], but modified according to the needs of the project. The result from the critical appraisal will be reported on domain and overall level.

External validity

Applicability is one important aspect of external study validity, i.e., the degree to which the studies are appropriate or applicable for answering the review question in a particular context. This is to some extent assessed during study eligibility screening. However, the aspect of external validity that needs to be accounted for when evaluating the strength of evidence is the transferability of study results from studies with important differences such as, countries that differ in their treatment processes for sewage sludge, different soil properties or different farming practices compared to Sweden. Studies will not be excluded based on the location of the study, but we will record the location and differences in the concentration of contaminants in the sludge of included studies to be able to perform subgroup analyses or meta-regression and assess the overall transferability of the evidence base to the Swedish context.

Coding for study validity assessment

To ensure consistency in judgements in the critical appraisal, all team members will first do an assessment of a subset of articles, and decisions will be discussed among all authors. After consensus has been reached regarding our interpretation of the criteria, the risk of bias assessment will from that point be carried out independently by two reviewers for each study. The reviewers will not be allowed to assess the validity of their own work.

If quantitative synthesis is feasible, a sensitivity analysis will be performed, comparing results with and without excluding studies with high risk of bias. Risk of bias may also be used as a categorical variable in meta-regressions. In addition, risk of bias of the results will be accounted for when evaluating the strength of evidence.

Studies judged to contain substantial errors, such as miscalculations or potentially fabricated data and studies that lack central information about the details of the study as well as retracted studies will be excluded from the analysis.

Synthesis methods

The metadata from the included studies will be summarized in tables and text. The purpose of the metadata table is to provide a quick overview of the key characteristics of each included study, including risk of bias assessments.

Separate analysis will be performed for sewage sludge as an intervention versus biochar derived from sewage sludge as well as for uptake in crops versus accumulation in soil.

Different concentration of contaminants in the sludge will be addressed through meta-regression. If sufficient data is available, meta-regression will be conducted on studies from countries with sludge management and agriculture practices similar to Sweden If sufficient studies are not available, the results will be discussed in relation to their transferability to the Swedish context.

Quantitative synthesis through meta-analysis will be performed using the Metafor package in R when at least three comparisons are available [33, 34]. Individual results based on less than four replicates will not be included in the analysis due to risk of low statistical reliability. We will combine data with similar intervention and control options as well as performing separate analysis on similar groups of crops and contaminants. In case of significant heterogeneity among study results, we will attempt to identify potential effect modifiers through meta-regressions and the variation in the results will be presented and discussed [33].

To assess the risk of publication bias, funnel plots and Egger's regression tests may be employed when at least 10 comparisons are available [33].

We will also perform sensitivity analyses. For example, meta-analyses may be performed with and without results from studies with a high risk of bias, or by removing outliers or one study at the time to see if the overall result is affected.

If quantitative synthesis is not possible but more than three studies present data on the same comparison, a narrative synthesis of the results will be carried out, where validity, heterogeneity of study results as well as size of the study are considered.

Conclusions and evidence grading

Conclusions will be based on results from the meta-analyses and narrative syntheses. These conclusions will be evidence-graded, i.e. we will describe how much confidence we have in the conclusions based on the size of the dataset underpinning the conclusion, if the studies have been conducted by different research groups and in various locations, the robustness of the result, the risk of bias of the studies, transferability to the Swedish context and consistency between studies. The method of grading is inspired by the GRADE: framework. The conclusions will be categorized into the following four levels, and the reasons for the decisions for each grading will be stated in a table or text:

- **When we state we are very certain**, it means we assess the evidence as robust and that future research is unlikely to affect the result.
- **When we say we are fairly certain**, it means we have identified some shortcomings in the evidence, but these are not considered to weaken the conclusion.
- **When we say we are less certain**, it is because we have identified shortcomings in the evidence that may weaken the conclusion, and the aggregated results may therefore be misleading.
- **When we use the word uncertain in a conclusion**, it means we have identified serious shortcomings.

Also, the stronger the evidence, the less likely it is that reported results will be affected by new research findings in the foreseeable future.

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Additional file 1. Search strategy and search results

Bibliographic databases used in searching for literature

Table S1:1. Bibliographic databases used in searching for literature

Database/platform	Publisher and URL
Web of Science[1)]	Clarivate Analytics, https://clarivate.com/products/web-of-science/
Scopus	Elsevier, https://www.scopus.com/
CAB Abstracts	Wolters Kluwer (Ovid), https://www.ovid.com/ovid/home/index.html
ProQuest[2)]	Clarivate, https://www.proquest.com/
PubMed	National Library of Medicine (NIH), https://pubmed.ncbi.nlm.nih.gov/
Overton	Overton, https://www.overton.io/

[1)] Web of Science Core Collection, including Science Citation Index Expanded (SCI-EXPANDED), Social Sciences Citation Index (SSCI), Arts & Humanities Citation Index (A&HCI), Conference Proceedings Citation Index- Science (CPCI-S), Conference Proceedings Citation Index- Social Science & Humanities (CPCI-SSH) and Emerging Sources Citation Index (ESCI).

[2)] Agriculture Science Collection including AGRICOLA and Agriculture Science Database

Search strings

Bibliographic databases

Table S1:2. Combined search string used in Web of Science Core Collection

No	Terms
1	TI=("Agriculture" OR "Agroecosystem" OR "Agroecosystems" OR "Arable" OR "Crop" OR "Crops" OR "Plant" OR "Plants" OR "Soil" OR "Soils") OR AB=("Agriculture" OR "Agroecosystem" OR "Agroecosystems" OR "Arable" OR "Crop" OR "Crops" OR "Plant" OR "Plants" OR "Soil" OR "Soils") OR AK=("Agriculture" OR "Agroecosystem" OR "Agroecosystems" OR "Arable" OR "Crop" OR "Crops" OR "Plant" OR "Plants" OR "Soil" OR "Soils")
2	TI=("Biosolid" OR "Biosolids" OR "Sewage Sludge" OR "Sewage Sludges" OR "Sewage-Sludge" OR "Sewage-Sludges" OR "Sludge Fertiliser" OR "Sludge Fertilisers" OR "Sludge Fertilizer" OR "Sludge Fertilizers" OR "Waste Water Sludge" OR "Waste Water Sludges" OR "Wastewater Sludge" OR "Wastewater Sludges") OR AB=("Biosolid" OR "Biosolids" OR "Sewage Sludge" OR "Sewage Sludges" OR "Sewage-Sludge" OR "Sewage-Sludges" OR "Sludge Fertiliser" OR "Sludge Fertilisers" OR "Sludge Fertilizer" OR "Sludge

	Fertilizers" OR "Waste Water Sludge" OR "Waste Water Sludges" OR "Wastewater Sludge" OR "Wastewater Sludges") OR AK=("Biosolid" OR "Biosolids" OR "Sewage Sludge" OR "Sewage Sludges" OR "Sewage-Sludge" OR "Sewage-Sludges" OR "Sludge Fertiliser" OR "Sludge Fertilisers" OR "Sludge Fertilizer" OR "Sludge Fertilizers" OR "Waste Water Sludge" OR "Waste Water Sludges" OR "Wastewater Sludge" OR "Wastewater Sludges")
3	TI=("Accumulate" OR "Accumulated" OR "Accumulation" OR "Bioaccumulate" OR "Bioaccumulated" OR "Bioaccumulating" OR "Bioaccumulation" OR "Concentration" OR "Concentrations" OR "Increase" OR "Increased" OR "Increases" OR "Increasing" OR "Level" OR "Levels" OR "Transfer" OR "Transferred" OR "Transferring" OR "Uptake" OR "Uptakes") OR AB=("Accumulate" OR "Accumulated" OR "Accumulation" OR "Bioaccumulate" OR "Bioaccumulated" OR "Bioaccumulating" OR "Bioaccumulation" OR "Concentration" OR "Concentrations" OR "Increase" OR "Increased" OR "Increases" OR "Increasing" OR "Level" OR "Levels" OR "Transfer" OR "Transferred" OR "Transferring" OR "Uptake" OR "Uptakes") OR AK=("Accumulate" OR "Accumulated" OR "Accumulation" OR "Bioaccumulate" OR "Bioaccumulated" OR "Bioaccumulating" OR "Bioaccumulation" OR "Concentration" OR "Concentrations" OR "Increase" OR "Increased" OR "Increases" OR "Increasing" OR "Level" OR "Levels" OR "Transfer" OR "Transferred" OR "Transferring" OR "Uptake" OR "Uptakes")
4	1 **AND** 2 **AND** 3

TI= Title

AB= Abstract

AK= Author Keywords

" " = Phrase searching, retrieve words in that exact order

Table S1:3. Combined search string used in Scopus

No	Terms
1	(TITLE ({Agriculture} OR {Agroecosystem} OR {Agroecosystems} OR {Arable} OR {Crop} OR {Crops} OR {Plant} OR {Plants} OR {Soil} OR {Soils}) OR ABS ({Agriculture} OR {Agroecosystem} OR {Agroecosystems} OR {Arable} OR {Crop} OR {Crops} OR {Plant} OR {Plants} OR {Soil} OR {Soils}) OR AUTHKEY ({Agriculture} OR {Agroecosystem} OR {Agroecosystems} OR {Arable} OR {Crop} OR {Crops} OR {Plant} OR {Plants} OR {Soil} OR {Soils}))
2	(TITLE ({Biosolid} OR {Biosolids} OR {Sewage Sludge} OR {Sewage Sludges} OR {Sewage-Sludge} OR {Sewage-Sludges} OR {Sludge Fertiliser} OR {Sludge Fertilisers} OR {Sludge Fertilizer} OR {Sludge Fertilizers} OR {Waste Water Sludge} OR {Waste Water Sludges} OR {Wastewater Sludge} OR {Wastewater Sludges}) OR ABS ({Biosolid} OR {Biosolids} OR {Sewage Sludge} OR {Sewage Sludges} OR {Sewage-Sludge} OR {Sewage-Sludges} OR {Sludge Fertiliser} OR {Sludge Fertilisers} OR {Sludge Fertilizer} OR {Sludge Fertilizers} OR

	{Waste Water Sludge} OR {Waste Water Sludges} OR {Wastewater Sludge} OR {Wastewater Sludges}) OR AUTHKEY ({Biosolid} OR {Biosolids} OR {Sewage Sludge} OR {Sewage Sludges} OR {Sewage-Sludge} OR {Sewage-Sludges} OR {Sludge Fertiliser} OR {Sludge Fertilisers} OR {Sludge Fertilizer} OR {Sludge Fertilizers} OR {Waste Water Sludge} OR {Waste Water Sludges} OR {Wastewater Sludge} OR {Wastewater Sludges}))
3	(TITLE ({Accumulate} OR {Accumulated} OR {Accumulation} OR {Bioaccumulate} OR {Bioaccumulated} OR {Bioaccumulating} OR {Bioaccumulation} OR {Concentration} OR {Concentrations} OR {Increase} OR {Increased} OR {Increases} OR {Increasing} OR {Level} OR {Levels} OR {Transfer} OR {Transferred} OR {Transferring} OR {Uptake} OR {Uptakes}) OR ABS ({Accumulate} OR {Accumulated} OR {Accumulation} OR {Bioaccumulate} OR {Bioaccumulated} OR {Bioaccumulating} OR {Bioaccumulation} OR {Concentration} OR {Concentrations} OR {Increase} OR {Increased} OR {Increases} OR {Increasing} OR {Level} OR {Levels} OR {Transfer} OR {Transferred} OR {Transferring} OR {Uptake} OR {Uptakes}) OR AUTHKEY ({Accumulate} OR {Accumulated} OR {Accumulation} OR {Bioaccumulate} OR {Bioaccumulated} OR {Bioaccumulating} OR {Bioaccumulation} OR {Concentration} OR {Concentrations} OR {Increase} OR {Increased} OR {Increases} OR {Increasing} OR {Level} OR {Levels} OR {Transfer} OR {Transferred} OR {Transferring} OR {Uptake} OR {Uptakes}))
5	1 **AND** 2 **AND** 3

TITLE= Title

ABS= Abstract

AUTHKEY= Author Keywords.

{ } = Phrase searching, retrieve words in that exact order

Table S1:4. Combined search string used in CAB Abstracts

No	Terms
1	("Agriculture" or "Agroecosystem" or "Agroecosystems" or "Arable" or "Crop" or "Crops" or "Plant" or "Plants" or "Soil" or "Soils").ab,ti.
2	("Biosolid" or "Biosolids" or "Sewage Sludge" or "Sewage Sludges" or "Sewage-Sludge" or "Sewage-Sludges" or "Sludge Fertiliser" or "Sludge Fertilisers" or "Sludge Fertilizer" or "Sludge Fertilizers" or "Waste Water Sludge" or "Waste Water Sludges" or "Wastewater Sludge" or "Wastewater Sludges").ab,ti.
3	("Accumulate" or "Accumulated" or "Accumulation" or "Bioaccumulate" or "Bioaccumulated" or "Bioaccumulating" or "Bioaccumulation" or "Concentration" or "Concentrations" or "Increase" or "Increased" or "Increases" or "Increasing" or "Level" or "Levels" or "Transfer" or "Transferred" or "Transferring" or "Uptake" or "Uptakes").ab,ti.
4	("Journal article" or "Conference paper").pt.
5	(English or Swedish or Norwegian or Danish or German or French or Finnish).lg.

6	1 **AND** 2 **AND** 3 **AND** 4 **AND** 5

ti. = Title

ab.= Abstract

pt.= Publication Type

lg.=Language

" " = Phrase searching, retrieve words in that exact order

Table S1:5. Combined search string used in ProQuest

No.	Terms
1	title("Agriculture" OR "Agroecosystem" OR "Agroecosystems" OR "Arable" OR "Crop" OR "Crops" OR "Plant" OR "Plants" OR "Soil" OR "Soils") OR abstract("Agriculture" OR "Agroecosystem" OR "Agroecosystems" OR "Arable" OR "Crop" OR "Crops" OR "Plant" OR "Plants" OR "Soil" OR "Soils") OR if("Agriculture" OR "Agroecosystem" OR "Agroecosystems" OR "Arable" OR "Crop" OR "Crops" OR "Plant" OR "Plants" OR "Soil" OR "Soils")
2	title("Biosolid" OR "Biosolids" OR "Sewage Sludge" OR "Sewage Sludges" OR "Sewage-Sludge" OR "Sewage-Sludges" OR "Sludge Fertiliser" OR "Sludge Fertilisers" OR "Sludge Fertilizer" OR "Sludge Fertilizers" OR "Waste Water Sludge" OR "Waste Water Sludges" OR "Wastewater Sludge" OR "Wastewater Sludges") OR abstract("Biosolid" OR "Biosolids" OR "Sewage Sludge" OR "Sewage Sludges" OR "Sewage-Sludge" OR "Sewage-Sludges" OR "Sludge Fertiliser" OR "Sludge Fertilisers" OR "Sludge Fertilizer" OR "Sludge Fertilizers" OR "Waste Water Sludge" OR "Waste Water Sludges" OR "Wastewater Sludge" OR "Wastewater Sludges") OR if("Biosolid" OR "Biosolids" OR "Sewage Sludge" OR "Sewage Sludges" OR "Sewage-Sludge" OR "Sewage-Sludges" OR "Sludge Fertiliser" OR "Sludge Fertilisers" OR "Sludge Fertilizer" OR "Sludge Fertilizers" OR "Waste Water Sludge" OR "Waste Water Sludges" OR "Wastewater Sludge" OR "Wastewater Sludges")
3	title("Accumulate" OR "Accumulated" OR "Accumulation" OR "Bioaccumulate" OR "Bioaccumulated" OR "Bioaccumulating" OR "Bioaccumulation" OR "Concentration" OR "Concentrations" OR "Increase" OR "Increased" OR "Increases" OR "Increasing" OR "Level" OR "Levels" OR "Transfer" OR "Transferred" OR "Transferring" OR "Uptake" OR "Uptakes") OR abstract("Accumulate" OR "Accumulated" OR "Accumulation" OR "Bioaccumulate" OR "Bioaccumulated" OR "Bioaccumulating" OR "Bioaccumulation" OR "Concentration" OR "Concentrations" OR "Increase" OR "Increased" OR "Increases" OR "Increasing" OR "Level" OR "Levels" OR "Transfer" OR "Transferred" OR "Transferring" OR "Uptake" OR "Uptakes") OR if("Accumulate" OR "Accumulated" OR "Accumulation" OR "Bioaccumulate" OR "Bioaccumulated" OR "Bioaccumulating" OR "Bioaccumulation" OR "Concentration" OR

	"Concentrations" OR "Increase" OR "Increased" OR "Increases" OR "Increasing" OR "Level" OR "Levels" OR "Transfer" OR "Transferred" OR "Transferring" OR "Uptake" OR "Uptakes")
4	1 **AND** 2 **AND** 3

title= Title

abstract= Abstract

if= Keywords

" " = Phrase searching, retrieve words in that exact order

Table S1:6. Combined search string used in PubMed

No.	Terms
1	"Biosolids"[MeSH Terms] OR "Sewage"[MeSH Terms]
2	"Crop Production"[MeSH Terms] OR "crops, agricultural"[MeSH Terms] OR "Plants"[MeSH Terms:noexp] OR "plants, edible"[MeSH Terms] OR "Soil Pollutants"[MeSH Terms:noexp]
3	1 **AND** 2

Mesh = MeSH (Medical Subject Headings) is the NLM controlled vocabulary thesaurus used for indexing articles for PubMed

Table S1:7. Preliminary searches in Overton

Language	Search Fields	Filters	Terms
English	Title	Language: English, French. German	("Sewage Sludge" OR Biosolids) AND (Uptake OR Concentration* OR Transfer* OR Transferring OR Increasing OR Increase*)
English	Abstract	Language: English, French. German	("Sewage Sludge" OR Biosolids) AND (Uptake OR Concentration* OR Transfer* OR Transferring OR Increasing OR Increase*)
Swedish	Title	Language: Swedish	(Slam OR Avloppsslam OR Biomull)
Swedish	Abstract	Language: Swedish	(Slam OR Avloppsslam OR Biomull)

Table S1:8. Preliminary search results in bibliographic databases

Database/platform	Date	Retrieved records in database	Records after deduplication
Web of Science	2025-09-01	11 754	11 349
Scopus	2025-08-29	13 460	2 321

CAB Abstracts	2025-09-01	10 567	1 088
ProQuest	2025-09-01	6 750	161
PubMed	2025-09-01	2 335	1 302
Overton	2025-09-01	181	81
Total		**45 047**	**16 302**

Archives and Search Engines used in searching for literature

Table S1:9. Archives and Search Engines used in searching for literature

Database/platform	Publisher and URL
BASE	Bielefeld Academic Search Enginge, https://www.base-search.net/
Swepub	Kungliga biblioteket, https://swepub.kb.se/
Google Scholar	Google, https://scholar.google.com/
OpenAlex	OurResearch, https://openalex.org/

Table S1:10. Preliminary searches in BASE

Language	Search Fields	Filters	Terms
English	Advanced Search, All fields	Report + Book chapter	("Sewage Sludge" OR Biosolids) AND (Uptake OR Transfer) AND (Crop* OR Plant* OR Soil*)
Swedish	Advanced Search, All fields	Report + Book chapter	(Avloppsslam OR Biomull) AND (växt*)
Swedish	Advanced Search, All fields	X	(Avloppsslam OR Biomull) AND (Upptag OR Överför*)

Table S1:11. Preliminary searches in Swepub

Language	Search Fields	Filters	Terms
English	All fields	Report + Book chapter	("Sewage Sludge" OR Biosolids) AND (Crop* OR Plant* OR Soil*)
English	All fields	Report + Book chapter	("Sewage Sludge" OR Biosolids) AND (Uptake OR Transfer)

Swedish	All fields		(Avloppsslam OR Biomull) AND (växt*)
Swedish	All fields		(Avloppsslam OR Biomull) AND (Upptag OR Överför*)

Table S1:12. Preliminary searches in Google Scholar

Language	Terms
English	Sewage Sludge Uptake OR Transfer
English	Sewage Sludge Crop* OR Plant*OR Soil
English	Biosolids Uptake OR Transfer
English	Biosolids Crop* OR Plant* OR Soil
Swedish	Avloppsslam Upptag OR Överförs
Swedish	Avloppsslam Växter
Swedish	Biomull Upptag OR Överförs
Swedish	Biomull Växter

Table S1:13. Preliminary searches in OpenAlex

Language	Search Fields	Filters	Terms
English	Report + Book chapter	x	("Sewage Sludge" OR Biosolids) **AND** (Uptake OR Transfer) **AND** (Crop* OR Plant* OR Soil*)
Swedish	Report + Book	x	Avloppsslam OR Biomull

Table S1:14. Preliminary search results in archives and search engines

Platform	Date	Retreieved records in database	Records after deduplication
BASE	2025-09-02	153	63
Google Scholar*	2025-09-03	805	408
SwePub	2025-09-03	92	58
OpenAlex	2025-09-02	194	46
Total		**1244**	**575**

* More than 805 records were retrieved, but not all were imported into EndNote.

References, total after deduplication = 16 877

Test references to assess comprehensiveness of the searches

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