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Utilization of sewage sludge to manage saline–alkali soil and increase crop production: Is it safe or not?

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ABSTRACT

Saline–alkali soil has become a significant problem for global agriculture and food security as these soils have poor physicochemical conditions and reduce crop production by causing a wide range of physiological and biochemical changes in plants. More than 800 million hectares (Mha) of land throughout the world are affected by saline–alkali soil, which accounts for 6% of the world total land area, and about 62 Mha or 20% of the world's irrigated land is affected by saline–alkali soil. Numerous studies on saline–alkali soils have been conducted throughout the years in an attempt to reduce plant productivity losses. Utilizing sewage sludge (SS) is an efficient way to improve saline–alkali soil and its physiochemical properties for plant productivity and improve soil's health and crop yield. However, the in-depth mechanisms for the utilization of sewage sludge, their nutrient levels, toxic and harmful substances such as heavy metals, pathogenic microorganisms, antibiotics, and resistant genes that affect crop yield, groundwater quality, and ecological risks are still uncertain. This review enhances the awareness and knowledge to explore the sustainable mode of SS utilization in saline–alkali soil for the crop growth with crop rhizosphere effect, saline–alkali soil micro-ecology, carbon and nitrogen cycle enhancement. The potential future perspectives and research limitations for the utilization of SS for the crop production in saline–alkali soil are also discussed in review article.

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Acronyms and Abbreviations

$\text{Al}_2(\text{SO}_4)_3$	Aluminum sulfates
ARGS	Antibiotic Resistance Genes
AS	Activated Sludge
As	Arsenic
B	Boron
Ca^{2+}	Calcium
Cd^{2+}	Cadmium
C–GT	Carver–Greenfield Technology
Cl^-	Chloride
CO_2	Carbon Dioxide
Co^{2+}	Cobalt
CO_3^{2-}	Carbonate Ions
Cr^{2+}	Chromium
Cu^{2+}	Copper
DEH	4-Deoxy-L-Erythro-5-Hexoseulose Uronate
dS cm^{-1}	Decisiemens per centimeter
dS/m	Decisiemens per meter
EC	Electric Conductivity
ESP	Exchangeable Sodium Percentage
FAO	Food And Agricultural Organization
FD	Fluidized Bed

Fe ²⁺	Iron
GHGs	Greenhouse Gases
GMs	Geomaterials
GRT	Gas Residence Time
HCO ₃ [−]	Bicarbonate
Hg ²⁺	Mercury
HMs	Heavy metals
HR	Heating Rate
HWSD	Harmonized World Soil Database
K ⁺	Potassium
K ₂ O	Potassium oxide
Mg ²⁺	Magnesium
MgO	Magnesium Oxide
Mha	Million hectares
N ₂ O	Nitrous oxide
Na ⁺	Sodium
NACWA	National Association Of Clean Water Agencies
NBC	Nano-biochar
NHAP	Nano Hydroxyapatite
Ni ²⁺	Nickel
NO ₃ [−]	Nitrate
NOx	Nitrogen oxides
NPs	Nanoparticles
OFS	Oil-From-Sludge
OM	Organic Matter
P ₂ O ₅	Phosphorus
PAH	Polycyclic Aromatic Hydrocarbons
Pb ²⁺	Lead
PCB	Polychlorinated Biphenyls
PS	Primary Sludge
PTEs	Potential Toxics Elements
PVC	Polyvinyl Chloride
SAR	Sodium Adsorption Ratio
SARS-CoV-2	Severe Acute Respiratory Syndrome Coronavirus 2.
SiO ₂	Silica
SO ₄ ^{2−}	Sulfate
SOM	Soil Organic Matter
Sox	Sulfur oxides
SS	Sewage Sludge
SSBT	Siemens Schwell–Brenna Technology
T Ha ^{−1}	Tonnes Per Hectare
TDS	Total Dissolved Solids
TiO ₂	Titanium dioxide
WAS	Waste Activated Sludge
WWTP	Waste Water Treatment Plant
Zn ²⁺	Zinc

1. Introduction

Saline–alkali soil is one of the main environmental factors affecting crop productivity, especially in arid and semi-arid areas (Zhang, 2008, 2020a,b). Due to global industrialization, unplanned urbanization, climate change, and different types of soil degradation, the accessibility of soil for agriculture is rapidly decreasing, particularly in developing countries (Jia et al., 2023; Ma and Tashpolat, 2023; Mukhopadhyay et al., 2021; Pitman and Läuchli, 2002; Khan and Shoumik, 2022). The anion such as calcium (Ca²⁺), magnesium (Mg²⁺) iron (Fe²⁺), sodium (Na⁺), potassium (K⁺) and cations such

Table 1

Classification of saline-alkali soil based on physiochemical properties modified from Scherer et al. (1996) and Alonge et al. (2018).

Characteristics	Saline soil	Alkali soil
pH	<8.5	8.5–10.0
EC (dS m ⁻¹)	>4	<4
ESP (%)	<15	>15
Presence of cations/anions	Na ⁺ , K ⁺ , Ca ²⁺ , Mg ²⁺ , SO ₄ ²⁻ , and Cl ⁻	Carbonate ions CO ₃ ²⁻ of Na ⁺
SAR (mmol _c kg ⁻¹)	<13	>13
Color	White colored, thus referred to as white alkali soils	Black colored, thus referred to as black alkali soils
Also known as	Solonchaks	Solonetz
Description	Smooth soil surface, apparent salt layer, surface salt buildup, sluggish or no germination, very limited plant growth.	Shallow plant roots, puddles of turbid water on the surface of the soil, different crop growth rates, etc.

as, carbonate (CO₃²⁻), bicarbonate (HCO₃⁻), chloride (Cl⁻), sulfate (SO₄²⁻) and nitrate (NO₃⁻) are the essential sources of salinity; nevertheless, sodium salts are the most common cause of salinity in soils (Rengasamy, 2006), and it has a negative impact on agricultural plants physiological and biochemical pathways (Nabati et al., 2011). The most prominent environmental factor is salt stress that restricts plants growth, development, and crop yield (Hu and Schmidhalter, 2023; Zörb et al., 2019). Soil salinization is a significant risk to soil functions listed recently reported by the Food and Agricultural Organization (FAO) (FAO, 2015a,b). The excess sodium ions (Na⁺) induces cytosolic potassium (K⁺) and Ca²⁺ outflow, causing an imbalance in their cellular equilibrium, nutritional deficiency, oxidative stress, delayed growth, and cell death (Ahanger and Agarwal, 2017).

The amount of salt in the soil has been getting worse in the last few years, more than 800 million hectares (Mha) of land throughout the world affected by saline-alkali soil, which accounts for 6% of the world total land area (Dagar et al., 2019; Gopalakrishnan and Kumar, 2020; Zaman et al., 2018). Thus, the saline-alkali soil problems are increasing, and making insufficient food in several countries it is estimated that currently about 62 Mha or 20% of the world's irrigated land is affected directly impacts on crop yield (Bennett et al., 2009; Rengasamy, 2016; Zaman et al., 2018; Zörb et al., 2019). According to calculation by Sandra (1989), approximately 25% of the world's irrigated lands are negatively impacted by salt. However, Adams and Hughes (1990) have reported a higher number, suggesting that up to 50% of irrigated lands are affected by salt. Szabolcs (1989) declared that salt-affected soils are present in every continent, and at least 70 countries experience significant problems related to salt. The recently studies investigate that the world's total area of salt-affected soil is around 1125 million hectares (Mha) (Hossain, 2019). According to the FAO Land and Nutrition Management Service (2008), more than 831 Mha of agricultural land is salt-affected on the global level (FAO, 2008); out of that saline affected land are 397 Mha (47.8%), while alkali affected land are 434 Mha (52.2%) (Martinez-Beltran, 2005; Setia et al., 2013). Out of the total cultivated and irrigated agricultural land, 50% is affected by high saline-alkali soil on global level (Gengmao et al., 2015). Due to increasing soil salinity, three hectares of arable soil are degraded every minute, posing a severe threat to global food security (Pisinaras et al., 2010; Zaman et al., 2018). At this rate more than 50% of arable land would be salinized by 2050 (Jamil et al., 2011). The irrigation with saline water, low precipitation, and high evapotranspiration are key factors that cause salinization at a rate of 10% annually to agricultural lands. Even 30% of irrigated soil in regions like the Middle East, North America, and Oceania affected (Goossens and Van Ranst, 1998; Shrivastava and Kumar, 2015). The world distribution of saline and alkali soil is shown in Fig. 1a, b. The effects of saline-alkali soils in these regions are caused by the deposition of salts released from in soil seas, parent rock, historical drainage basins and a lack of adequate natural drainage (Bhattacharyya et al., 2015).

The characteristics of saline-alkali soils are commonly used to describe pH, electrical conductivity (EC), exchangeable sodium percentage (ESP), and sodium adsorption ratio (SAR). Saline soil comprises soluble salts and the pH < 8.5, EC > 4 dS/m, ESP < 15 and SAR < 13; nevertheless, sulfate and chloride ions often predominate. It has a poor exchangeable sodium content and due to excess soluble salts, a white-colored salt crust forms at the soil surface when evaporation rate is too high; hence, it is also called white alkali soil. However, the alkali soil comprises superfluous exchangeable sodium ions and pH > 8.5, EC < 4 dS/m, ESP > 15, SAR > 13. These soils are also known as solonetz, it is black; thus, it is also known as black alkali. Allison and Richards (1954) developed the definition of salt-affected soil characteristics by using measurable soil variables. For the salt-affected soil classes, Abrol et al. (1988) proposed a pH limit of 8.2 rather than 8.5 in response to the Allison and Richards (1954) restrictions. These characteristics have often been employed to classify soils affected by salt, the classification of saline and alkali soils are shown in Table 1. Moreover, according to Szabolcs (1987) saline soils can be classed as potentially saline, Gypsisferous, or depending on the soluble ions, such as Ca²⁺, soluble Mg²⁺, Fe²⁺ and aluminum sulfates Al₂(SO₄)₃, chloride (Cl⁻), etc. Table 2 shows the degree of saline-alkali concerns in soil is typically categorized using weight, electrical conductivity, and exchangeable sodium ions (Abrol et al., 1988; Allison and Richards, 1954; Amrhein, 1996; FAO, 2008; Jahn et al., 2006) and chinese classification of soil in coastal, semi-humid, semi-arid, arid regions and semi-desert and desert regions (Zunqin et al., 1993).

Agricultural risks from saline-alkali soil with toxic ions and poor growth conditions severely restrict nutrient cycling, reducing crop production (Rasouli et al., 2013; Setia et al., 2013). The economic impact of saline-alkali soil induced yield

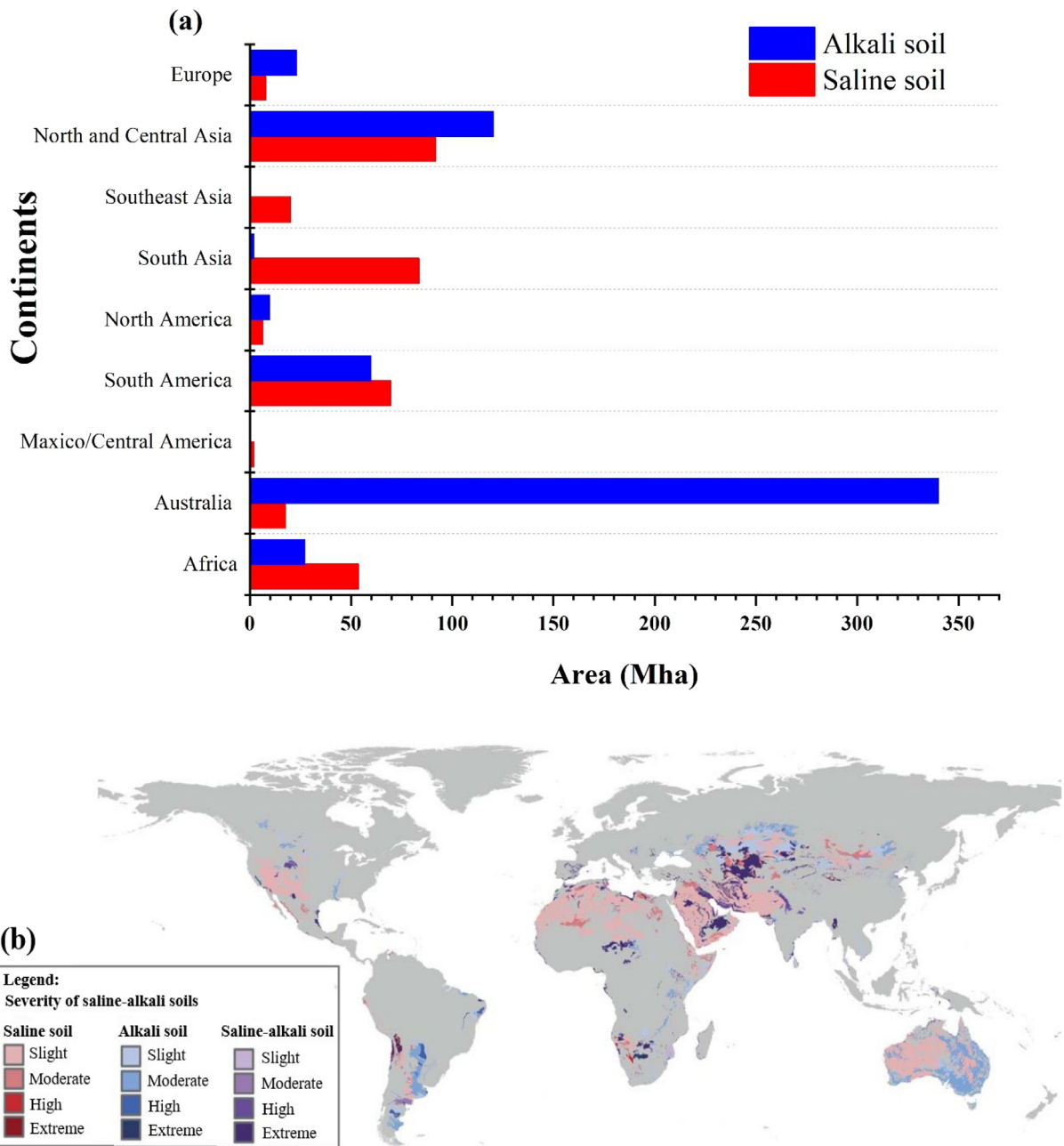


Fig. 1. (a) Area (Mha) of saline-alkali soil in different continents data collected from [FAO \(2015a,b\)](#) (b) Global saline-alkali soil by type and severity based on data from the Harmonized World Soil Database (HWSD) ([FAO, 2012](#); [Wicke et al., 2011](#)).

losses on agriculture businesses; it is estimated that the economic effect of saline-alkali on irrigated soil exceeds 27 billion US dollars per year ([Qadir et al., 2014](#)). Several agricultural zones are at risk of zero yield due to soil salinization ([Qadir et al., 2006](#)). An area of 6.10 Mha of the total 14.10 Mha of agricultural land accessible in the globe is either arid or semi-arid ([Christiansen, 1982](#)). Crop yield was evaluated in previous research for varying degrees of soil salinity. In corn, wheat, and cotton, moderate soil salinity of 8 to 10 dS m⁻¹ caused yield losses of correspondingly 55%, 28%, and 15%. Due to the higher soil salinity of 18 dS m⁻¹, cotton yield loss by 55% ([Satir and Berberoglu, 2016](#)). A vast majority of crops are extremely salt sensitive the proper techniques are needed to implement. Although high Na⁺ and Cl⁻ concentrations are harmful to plants, especially when they accumulate in the cytosol, diminutive is known about the cytosolic functions impeded by high salt ion concentrations, such as the toxicity of chloride in the cytosol ([Geilfus, 2018](#)). Ion-toxicities have several consequences, including an ionic imbalance in Na⁺ uptake that competes with the uptake of K⁺, Ca²⁺,

Table 2

Classifying severity of saline and alkali level in soil.

Severity	Saline soil (EC _e dS/m)		Alkali soil (ESP)	
	FAO (2008)	Allison and Richards (1954)	Abrol et al. (1988)	Amrhein (1996)
Extreme	>15		>70	>25
Very Strong	8–15	>16	50–70	15–25
Moderate	2–4	4–8	30–50	10–15
Slight	0.75–2	2–4	15–30	6–10
None	<0.75	0–2	<15	<6
Chinese classification of soil measured in gm of salt content per kg soil (g/kg) (Zunqin et al., 1993)				
Coastal, semi-humid, semi-arid, and arid regions			Semi-desert and desert regions	
Solonchak		>6		>5–10
Severe		4–6		5–10
Moderate		2–4		3–5
Light		1–2		2–3
None		<1.0		<2.0

and Mg^{2+} . Also, there is an acceleration of transpiring leaf senescence due to toxic concentrations of deleterious ions in photosynthetic active tissues and reduced availability of beneficial nutrients, thus to increase the agricultural/crop yield, it is required to manage the saline–alkali soil (Egamberdieva et al., 2019). Due to coastal soil salinization, the delta regions of India, Bangladesh, and Myanmar, which make substantial contributions to the world's rice production, are threatened with serious problems with food security (Abedin et al., 2014; Szabo et al., 2016). Ghassemi et al. (1995) reported that salt-affected irrigated lands cost the world economy \$12 billion US dollars in yearly income. Saline–alkali soil in the central California area of the United States causes an annual loss in crop yield of around \$3.7 billion US dollars (Dove, 2017). Salinity reduces crop production by 25% on average in the Alberta, the western province of Canada, and annual agricultural loss in Pakistan Sindh province area is 31% due to waterlogging and salinity (Ilyas, 2017).

Industrial wastewater refers to the liquid waste that contains substances that have been dissolved or suspended in water, typically resulting from the utilization of water in industrial production processes or the accompanying cleaning procedures (Woodard and Curran, 2006). Many industrial wastewaters, whether arising from manufacturing, agricultural, or food processing businesses, are polluted with potentially harmful ionic species such as toxic metals and bacteria. As a consequence, they represent a considerable hazard to human health and the environment (Izah et al., 2023). Domestic sewage is wastewater that is evacuated from homes, hotels, restaurants, schools, and retail centers on a regular basis. It has a broad variety of sources and a vast quantity. Domestic sewage is distinguished by a high concentration of pathogenic microbes, suspended materials, and organic stuff such as protein, carbohydrate, fat, and urea (Jiao, 2021). Two main types of domestic wastewater black water and gray water. Black water consists of the waste discharged from toilets and contains significant amounts of organic matter, nitrogen, and phosphorus. On the other hand, gray water refers to all other wastewater generated in households, such as from sinks, showers, and laundry, excluding toilet waste. Gray water volume is seven times higher than black water and typically contains lower levels of organic compounds, although some persistent molecules may still be present. Residential structures or homes account for approximately 75% of domestic wastewater production, while the remaining percentage comes from office buildings, commercial areas, public facilities, and the like. Although both household and non-household sources generate wastewater, the composition and quantity of domestic wastewater differ while sharing similar components (Widyarani et al., 2022). The Rural Ministry of Agriculture of China has banned the use of sewage sludge for agricultural production due to concerns over heavy metal contamination and other pollutants (Yang et al., 2015). In China, most of the sewage sludge is disposed of by improper dumping. However, some studies have shown that composted sewage sludge can be used as fertilizer in agriculture. During composting, straw, wood chips, bark, tree leaves, potassium fertilizer, and lime are added as bulking agents to improve the fertility of composted sludge (Zhihong, 1998).

Increasing crop yield to feed the rising population has been challenging since the beginning of agricultural techniques. Hence, developing strategies for managing saline–alkali soil will be crucial in tackling the issue of limited crop soil and meeting the task of providing food security for the world's projected 10 billion people by 2050 (Fischer et al., 2001; Konuma, 2018; Mukhopadhyay et al., 2021). Using sewage sludge (SS) is the best common technique for improving saline–alkali soils' physical and chemical properties and promoting plant production (Andriamananjara et al., 2016). Using SS on saline–alkali soil for crop production is beneficial, as shown in Fig. 2 and the nutritional content is generally considered sufficient for plant feeding (Fliessbach et al., 1994). Studies have investigated the efficacy of various organic materials, including sewage sludge, for remediating saline–alkali soil (Tejada et al., 2006; Walker and Bernal, 2008). Sewage sludge is a significant raw resource because it is a great source of plant nutrients and contains a high concentration of organic matter, humus content, phosphorus, nitrogen, and other micro and macro components (Madejón et al., 2001; Marschner et al., 2003). Organic carbon-enriched SS may significantly improve agricultural soil's physical, chemical, and biological properties. In addition, the usefulness of various organic additives, such as compost derived from municipal solid waste (MSW) or sewage sludge, for remediating salt-stressed soil has also been investigated (Tejada et al., 2006; Walker and Bernal, 2008). Many studies have found that chemical fertilizers, particularly phosphorus, may be efficiently substituted

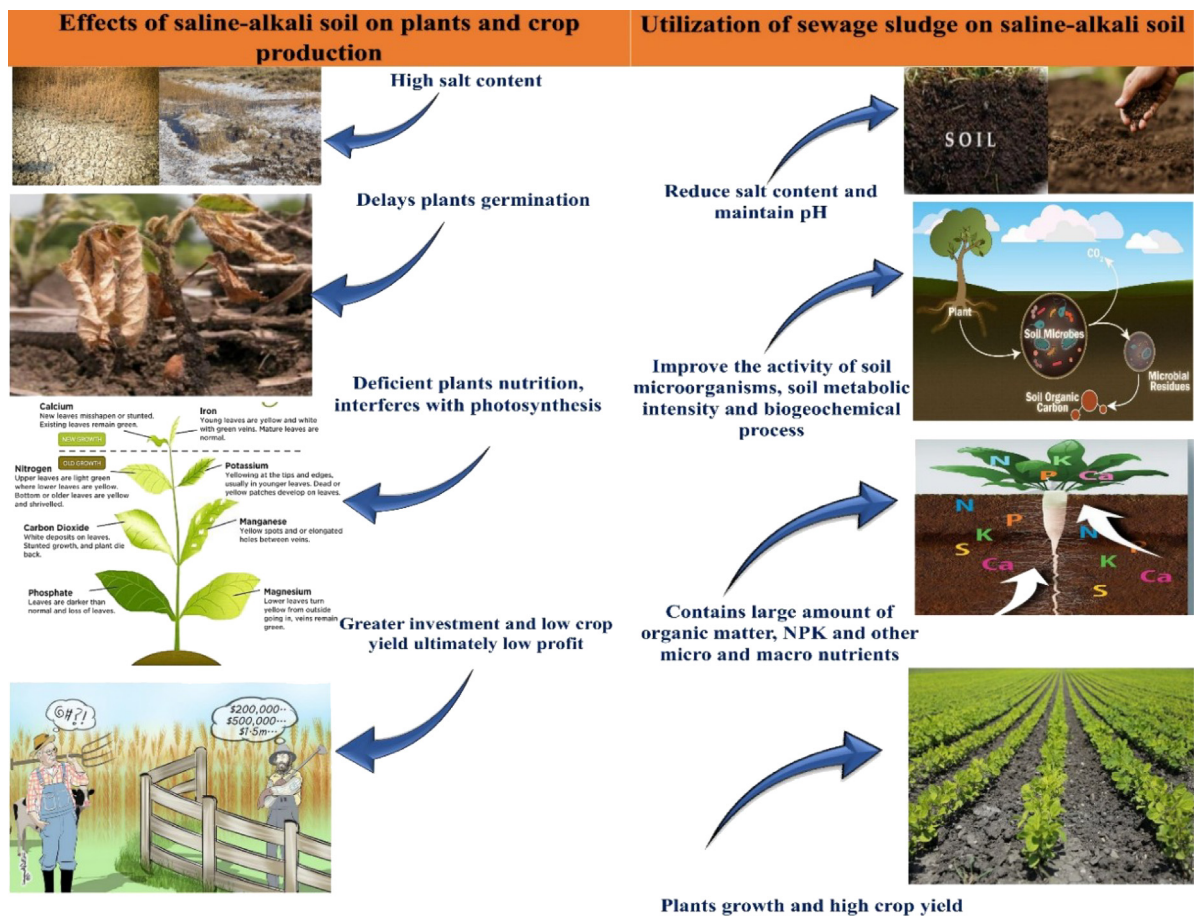


Fig. 2. Effects of saline-alkali soil Vs. Utilization of sewage sludge for crop productions.

with sewage sludge (Madejón et al., 2001; Marschner et al., 2003). Beneficial sludge contains up to 15% phosphorus (P_2O_5), 1% K^+ , and roughly 10% nitrogen (Fijalkowski et al., 2017). Sewage sludge can also stimulate soil respiration, and microorganism activity (Andriamananjara et al., 2016). Additionally, due to the lower costs, higher nutrient recovery, and simplicity of application, sewage sludge SS can be a great organic fertilizer and the organic content of SS improves saline-alkali soil biota, diversity, and nutrient storage and reduces erosion (Picariello et al., 2020). The physicochemical and biological characteristics of soil are altered by the gradual release of mineral components from SS, and the soil becomes improved (Cuevas et al., 2003). According to several studies, chemical fertilizers can be effectively replaced with SS, especially phosphorus. However, various site-specific aspects such as applied technology, quantity, and the source of raw wastewater vary by the macro- and microelements composition and hazard chemicals that make each SS unique. This individuality must be considered to determine the results of SS treatment (González et al., 2019). Therefore, sludge use has gained popularity as a resource due to the benefits of reclaiming plant nutrients and the ease of application and low cost.

Vieira and Pazianotto (2016) demonstrated that SS could enhance soil fertility and physicochemical properties that can consequently increase land capacity and soil structure. Many research works have shown that SS increases the physical and chemical characteristics of soil as well as microbiological activities (Ahmadpoor et al., 2011; Fernández-Luqueño et al., 2008; Koutroubas et al., 2023; Lakhdar et al., 2010; Shafieepour et al., 2011; Singh and Agrawal, 2008; Sousa and Figueiredo, 2016; Yue et al., 2017). Thus, it can improve agricultural production (Picariello et al., 2020; Rajput et al., 2022b; Tamrabet et al., 2009; Zhang et al., 2022). However, it is still unclear the effect of the absorption of nutrients by crops under multi-factor superposition stress; accumulation and transport of heavy metals (HMs) in the crop-soil-groundwater system can lead to environmental and ecological risks of soil/groundwater. This review paper focuses on sources and physicochemical characteristics of sewage sludge and the regulation for the safe and sustainable utilization of SS in saline-alkali soil for enhancing crop production. We also focuses on the utilization of SS and the mechanism for soil fertility, as well as providing future recommendation based on our theoretical discussions.

2. Sources and characteristics of sewage sludge

2.1. Sources of sewage sludge

Sludge refers to a mixture that is only partially solid and is produced by a variety of industrial processes such as the treatment of water or wastewater, as well as on-site sanitation systems. It can be created using, for instance, settled suspensions obtained from routine drinking water treatment processes, sewage sludge collected from wastewater treatment operations, or feces obtained from pit latrines and septic tanks (Raheem et al., 2018). Animal excrement is one of the main particles found in sludge. Sludge can be a potential organic fertilizers if it is composted because wastewater sludge is a rich source of nutrients, inorganic chemicals, and organic molecules. However, an excessive usage of uncontrolled wastewater could harm people's health and the climate as it may contain harmful pathogens or pollutants.

Since the amount of sludge has increased over the last few years, it has become a problem that needs solving. The United States produces around 10 Mt of dry sludge annually on average. In the European Union, it generates around 7.2 Mt of sludge solids annually. China produces 39 Mt of sludge annually (Kumar et al., 2021). The utilization and treatment process of this sludge has become a new dilemma these days. In a wastewater treatment plants (WWTPs), domestic and industrial wastewater must be treated via a primary sedimentation tank, an aeration tank, and a secondary sedimentation tank (Zhou et al., 2015).

Additionally, there are certain reimbursements for increasing food security, income opportunities, weather changes, and providing safe habitats for effective wastewater treatment (Corcoran, 2010). In Namibia, for example, 35% of all wastewater is treated, making it one of the many places in the world where filtered water has been effectively utilized for consumption (Association, 2013). In some underdeveloped countries, fecal sludge for wastewater treatment must be processed into dry fuel, such as briquettes (Logan et al., 2006). The main resources from wastewater treatment are irrigation and drinking water. Due to the minimal contamination of residential sanitation systems compared to bio solids from wastewater treatment facilities, feces are often utilized as fertilizer, particularly in septic systems. Certain treatment techniques absorb nutrients from wastewater's rich nitrate and phosphate structure during treatment, as opposed to treatment materials (Guest et al., 2009).

A highly complex mixture of molecules from proteins, peptides, lipids, polysaccharides, phenolic or aliphatic plant macromolecules (such as lignins or tannins), cutins or suberins, as well as organic micropollutants like polycyclic aromatic hydrocarbons (PAH) or dibenzofurans, are present in the undigested organic materials (Haghighat et al., 2020). Primary and secondary activated sludge properties are shown in Table 3. Primary SS is produced during mechanical wastewater treatment (screening, grit removal, and sedimentation). It typically comprises between 93% and 99.5% water and a high concentration of suspended and dissolved organic materials. Waste activated sludge (WAS), also known as secondary sludge, is generated during the biological treatment of wastewater and is primarily composed of microbial cells, which are polymeric organic molecules. The total solids content in secondary sludge varies from 0.8% to 1.2%, depending on the biological treatment method (Tezel et al., 2011a). The WAS contains 59 to 88% (w/v) organic material, which may decompose and emit unpleasant smells. Over 95% of the sludge is water, with only a minor portion solid. The organic component comprises 50–55 percent carbon, 30–35% oxygen, 15–20% nitrogen, 6%–10% hydrogen, 1%–3% phosphorus, and 0.5–1.5% sulfur (Orhon, 1997). Minerals such as quartz, calcite, or microline comprise most of the waste sludge's ash content. Fe^{2+} , Ca^{2+} , K^{2+} and Mg^{2+} are among the components that contribute to the formation of these minerals. Furthermore, the sludge contains heavy metals such as Chromium (Cr^{2+}), Nickel (Ni^{2+}), Copper (Cu^{2+}), Zinc (Zn^{2+}), Lead (Pb^{2+}), Cadmium (Cd^{2+}), and Mercury (Hg^{2+}) (Fonts et al., 2009). The combination of organic (volatile), inorganic matter (inert material), and wastewater in sludge determines their potential for crop production. The volatile solids, which are further split into easily degradable (50% in primary sludge and 25% in WAS) and not quickly degradable (30% in primary sludge and 55% in WAS), account for the majority of the sludge's energy content (Tezel et al., 2011a,b).

2.1.1. Treated domestic and industrial sludge

The US Environmental Protection Agency (EPA) states that utilizing treated domestic wastewater effluents and sludge on agricultural land can enhance crop production. Sewage sludge and wastewater effluents contain vital plant nutrients and improve the soil's physical condition, creating a more favorable environment for managing nutrients and water (Council, 1996; da Silva Oliveira et al., 2007; Feigin et al., 2012). However, applying industrial wastewater treated sewage sludge in farming may endanger the health and well-being of organisms exposed to contaminants over extended periods. Industrial sewage sludge contains heavy metals and antibiotics, which can interact and contribute to the emergence of bacterial resistance to these pollutants. Extensive environmental research and regulatory measures are necessary to minimize the risk of transferring these environmentally concerning pollutants and to understand their long-term effects. Improper or excessive application of industrial sewage sludge can result in nutrient imbalances, soil contamination, and the accumulation of heavy metals, all of which have detrimental effects on soil quality. Moreover, sludge may contain contaminants that can leach into water sources, posing risks to water quality. Previous studies have demonstrated that all pollutants are transferred to crops, posing a risk to consumers (Buta et al., 2021).

It is important to consider that the specific effects of treated domestic and industrial waste sludge can vary based on factors such as treatment processes, sludge characteristics, application methods, and local environmental conditions. Therefore, the presence of pollutants in treated industrial sewage sludge should be considered in the ongoing scientific discourse regarding the use of sewage sludge in agriculture. Thus, the proper treatment, management, and monitoring are crucial to mitigate potential negative effects and maximize the beneficial use of waste sludge while protection human health and the environment.

Table 3

Primary sludge (PS) and activated sludge (AS) characteristics (Tchobanoglus et al., 2003).

Parameters	PS	AS	Chemical composition
pH	5.0–8.0	6.5–8.0	Non-toxic organic carbon compounds (appx. 60% on dry basis), Kjeldhal-N, phosphorus-containing components.
Grease and fats (%TS)	7–35	5–12	
Protein (%TS)	20–30	32–41	
Alkalinity (mg/L as CaCO ₃)	500–1500	580–1100	Toxic pollutants: heavy metals such as, Zn ²⁺ , Pb ²⁺ , Cu ²⁺ , Cr ²⁺ , Ni ²⁺ , Cd ²⁺ , Hg ²⁺ , As: Initial concentration vary from 1000 mg/L to less than 1 mg/L, PCB, PAH, Dioxins, Pesticides, Endocrine disrupters, Nonyl-phenols.
Organic acids (mg/L as acetate)	200–2000	1100–1700	
Energy content (kJ/kg TS)	23,000–2900	19,000–23,000	
Silica (SiO ₂ %TS)	15–20	–	Pathogens and other microbiological pollutants.
Iron (Fe g/kg)	2–4	–	
Cellulose (%TS)	8–15	7–9.7	
Potash (K ₂ O %TS)	0–1	0.5–0.7	Inorganic compounds: Silicates, aluminates, Ca ²⁺ , and Mg ²⁺ , containing compounds.
Phosphorus (%TS)	0.8–2.8	0.5–0.7	
Nitrogen (%TS)	1.5–4	2.4–5.0	
Volatile solids, VS (%TS)	60–80	59–68	Water, varying from a few percent to more than 95%.
Total dry solids (total solids, TS) %	5–9	0.8–1.2	

2.2. Characteristics of sewage sludge

Sewage sludge is widely used in the agricultural sector as an organic fertilizer and for soil management. It can be a substitute for synthetic fertilizers reducing their requirements in the agricultural field (Mtshali et al., 2014). However, the application of sludge may have an adverse effect on the environment, especially if it contains HMs, organic pollutants, or pathogens. Hence, it is required to study the physical, chemical, and biological characteristics of sludge to know its surface properties, flocculating ability, nutrient content, probable HMs, and microbial activities.

The addition of municipal sludge can increase soil productivity by improving soil physical, chemical, and biological properties as sludge has a higher concentration of essential macro and micronutrients, organic carbon, and beneficial bacteria. Also, it may be a cost-effective organic fertilizer. Sustainable soil fertility may be promoted by adding organic matter like municipal sludge, potentially enhancing the soil's biological and physio-chemical characteristics. Various soil characteristics benefit from wastewater sludge's high concentrations of beneficial minerals and organic materials consequently, it may be a low-cost fertilizer. The separate discussions of the impact of sewage sludge on the physical, chemical, and biological soil characteristics are described as follow.

2.2.1. Physical characteristics of sewage sludge

The major physical characteristics of SS as a soil amendment include its density, porosity (void volume), water holding capacity, particle size distribution, flocculating ability, etc. Studies have revealed a lower bulk density of sewage sludge, and it depends on the sources of sludge materials, treatment process, water content, etc. For example, Angin and Yaghanoglu (2011) found a bulk density of 0.676 gm cm⁻³ in anaerobically digested sewage sludge, El-Nahhal et al. (2014) 1.18 gm cm⁻³, and Hu et al. (2012a) 1.05 gm cm⁻³ in wastewater treated sludge. It was explained that the decreased bulk density of sludge could be the result of higher porosity and the presence of water vapor and gas molecules inside the material. Without this, a higher water holding capacity and a lower filterability of sludge indicates a strong link to the capacity to bind water molecules and pore and particles size distribution. El-Nahhal et al. (2014) showed that the moisture retention capacity of sludge can be 2 times higher than a sandy soil, and they explained that the lesser permeability and more porosity could be responsible for higher water holding capacity. Moreover, water is present in four different forms in sludge materials, and they are interstitial water, capillary water, adhesive water, and internal water (Vaxelaire and Cézac, 2004). Among these four forms, capillary, adhesive, and internal forms are very difficult to separate. Another study conducted by found a series of different clusters with various pore sizes in sludge materials that ensured a higher void volume and lower bulk density (Ruan and Liu, 2013). They also showed the presence of high porosity in the sludge floc (a process of cluster-cluster flocculation), the gaps and holes on the floc surface, and the fractal structure with a size range between (0.5–50 μm). All these factors could be the reasons for lower density and high water retention capacity. Particle size is another important physical characteristic, but the distribution of particle size depends on the type of sludge and the presence of gravels. For instance, Guo et al. (2020) found that the particles larger than 500 μm was more dominant (>90%) in aerobic granular sludge selection discharge, while particles less than 500 μm was dominant in aerobic granular sludge mixture. However, in primary sludge, they found a small fraction of 500–2000 μm particles. El-Nahhal et al. (2014) showed the domination (nearly 90%) of larger particles (630–200 μm) compared to the medium-sized (200–20 μm) and fine-sized (<20 μm) particles. They highlighted that the domination of large particles could be due to the presence of aggregates, large sand fractions, or small gravels.

2.2.2. Chemical characteristics of sewage sludge

The chemical characteristics of sewage sludge mainly include pH, EC, organic carbon, and nutrient content. The pH of SS can be acidic to alkaline, but this pH range may differ based on the treatment and water content (El-Nahhal et al.,

Table 4
Concentration of different HMs in sludge (Geng et al., 2020).

Heavy metals	Concentration (mg/kg) in dry sludge
Arsenic	10
Cadmium	10
Chromium	500
Cobalt	30
Copper	800
Iron	17 000
Lead	500
Mercury	6
Molybdenum	4
Nickel	80
Selenium	5
Zinc	1700

2014) found that the pH of the wastewater treated sludge was 6.78, and Angin and Yaghanoglu (2011) found a pH of 6.82 in anaerobically digested SS. The presence of organic matter could be the reason for lower pH. Because when organic matter is decomposed and produces organic acids, they may become ionized and further produce hydrogen ions, which can increase acidity. A research conducted by Yuan et al. (2014) concluded that the ammonia nitrogen, short-chain fatty acids, and cations can be responsible for changing pH of sludge materials under different fermentation conditions. The electrical conductivity of sludge depends on presence of soluble salts. El-Nahhal et al. (2014) found an average EC value of 2.49 dS cm^{-1} , Suanon et al. (2016) found $>4 \text{ dS cm}^{-1}$ in wastewater treated sludge, while Novak and Trapp (2005) showed 14 dS cm^{-1} EC value in harbor sludge.

The organic matter and nutrient content of sludge vary depending on the treatment process and wastewater composition. Sharma et al. (2022) disclosed that the amount of organic matter in dewatered sludge ranges between 50 and 70%, minerals between 30 and 50%, nitrogen between 3 and 4%, phosphorus between 1 and 3%. They also showed that a well-managed SS could be useful for agricultural purposes because of its high organic matter and nutrient content, especially nitrogen and phosphorus. Other researchers also found a high amount of organic matter 70.5% (Wang et al., 2022) and 51.5% (Hurley et al., 2018). Nitrogen and phosphorus are found abundant in sewage sludge. Xu et al. (2012a,b) represented that sludge materials contain approximately 10% nitrogen as ammonium nitrogen and 10% phosphorus in water-soluble form. Another study conducted by Singh et al. (2022) showed that dry sludge may contain 2.35–4.2% nitrogen, 2.46–3.2% phosphorus, and 0.83–1.24% potassium, while sludge ash may contain around 14.6% phosphorus and 2.7% potassium making it an excellent organic fertilizer for growing crops. Besides these primary macronutrients (NPK), sludge also contain secondary macro and trace or micronutrients. However, their concentrations may vary depending on the sources of sludge materials and treatment processes.

Despite being a potential soil amendment, sludge can cause environmental pollution because of containing destructive chemical substances, like HMs and organic pollutants. The most common organic pollutants are polychlorinated biphenyls (PCBs) and dioxins. These compounds have higher lipid solubility but low water solubility which make them very hard to remove from environment. HMs enter into our environment through the haphazard disposal of industrial effluents, wastewater, or through the corrosion of sewerage systems and accumulate in the sludge. Geng et al. (2020) presented a probable and typical concentration of different HMs in sludge Table 4. Both HMs and organic pollutants easily bioaccumulate in the food chain an ecosystem and pose a serious environmental and human and animal health risk (Tytla, 2019).

2.2.3. Biological characteristics of sewage sludge

Sewage sludge floc is a multiphase medium with microbial aggregates, filamentous bacterial strains, organic and inorganic particles, and plenty of water (Guangyin and Youcai, 2017; Maw et al., 2022). Generally chemical properties of sludge, such as the macronutrient contents and pH (Wen-Feng et al., 2006); the presence of toxic elements, organic pollutants (Balcom et al., 2016; Bettiol and Ghini, 2011); and biological treatment (redox) conditions (Hu et al., 2012b) can directly influence the sludge bacterial community structure. A research showed by Cydzik-Kwiatkowska and Zielińska (2016) reported that many variables have been observed to influence structure of microbial community within WWTPs, which can shift from autotrophic to heterotrophic microorganisms depending on the effluent source. Most of the microorganisms found in urban WWTPs (household sewage) belonged to the phylum Proteobacteria 21%–65%, namely the Betaproteobacteria, which are involved in organic matter decomposition and nutrient cycling. There were also Bacteroidetes, Acidobacteria, and Chloroflexi, although they were far less numerous (Barnabé et al., 2008; Nielsen et al., 2010; Wan et al., 2011; Wang et al., 2012). Proteobacteria were also widespread in industrial effluent, which typically contained significant amounts of refractory chemicals from petroleum refineries, pharmaceutical businesses and other sources (Ibarbalz et al., 2013; Ma et al., 2015). The biological treatment conditions have a significant impact on the results. Studies have shown that microorganisms were more abundant in anaerobic than in aerobic systems (Hu et al., 2012b). However, it includes harmful bacteria, viruses, and protozoa, which can pose health risks to humans, animals, and plants (Yang et al., 2022). The amount of harmful and parasitic organisms in SS may be greatly decreased prior

to land application with adequate sludge treatment (Machnicka and Grübel, 2023). Pathogens in sewage and WWTP effluents have been reported to risk health of people and animals (Schöniger-Hekele et al., 2007; Sutherland et al., 2010). In addition, standards and regulations have not considered the pathogenic bacteria with antibiotic resistance genes (ARGs) that provide threat of antibiotic resistance. According to recent research, SARS-CoV-2 detection in sludge is easier than in sewage because sludge contains more virus particles and has longer residence times (Balboa et al., 2021). Because enteric viruses tend to aggregate and adhere to solid particles, it is believed that their stability and inactivation in SS differs from those in effluent (Bofill-Mas et al., 2006; Sidhu and Toze, 2009). There are two types of enteric viruses detected in SS samples: enteroviruses (poliovirus, coxsackievirus, and echovirus) and heterogeneous viruses (rotavirus, human caliciviruses, astroviruses, adenoviruses, and hepatitis A and E viruses). Usually, human adenoviruses are present in all types of sludge (Sidhu and Toze, 2009). In the recent research the, adenovirus was effectively found in various types of sludge with high occurrence (Assis et al., 2017; Bibby and Peccia, 2013; Jebri et al., 2012; Rhodes et al., 2015; Schlindwein et al., 2010; Wong et al., 2010).

Based on various literature reviews, it has been observed that the quantity of adenoviruses in sewage sludge can range from 2.5×10^3 genomic copy.g⁻¹ of dry weight in digested sludge samples to an average of 105 genomic copy.ml⁻¹ in activated sludge samples (Assis et al., 2017; Rhodes et al., 2015; Schlindwein et al., 2010). The adenovirus in primary sludge reported 104 to 105 genomic copy.L⁻¹ (Prado et al., 2014). Human adenoviruses are typically detected in large levels 103–108 infectious units/L in untreated wastewater (Rames et al., 2016). Adenovirus is recognized as an emerging pathogen due to its high resistance and prevalence, as well as the detection of the infectious virus in both treated drinking water and wastewater (Hewitt et al., 2013). Adenoviruses are more strong and have harmful for environmental conditions than other viruses (Gholipour et al., 2021). Adenovirus perseverance is related to a long life time of 301 days in viral-contaminated purified surface water and 132 days in wastewater (Wong et al., 2012).

3. Factors affecting the dynamics of sewage sludge in soil

3.1. Dose of sewage sludge

The optimum dosage of sewage sludge for saline–alkali soil depends on factors such as sludge quality, soil type, crop, and local regulations (Ahmed et al., 2010). The dosage is typically determined based on the nutrient content of the sludge, which are beneficial for plant growth (Casado-Vela et al., 2007). The previous study determine the effect of various sewage sludge dosages on sweet sorghum yields, quality, and soil attributes. In a three-year field experiment, three sorghum cultivars (GK Csaba, Róna 1, Sucrosorgo 506) were studied, and it was discovered that higher dosages of sewage sludge resulted in enhanced biomass yield. The differences in yields among the varieties were related to the level of sludge fertilization, with Sucrosorgo 506 performing best with higher sludge doses, GK Csaba with a moderate dose, and Róna 1 with lower sludge doses. With increasing sludge dosages, the content, absorption, and bioaccumulation of nutrients and heavy metals in the sludge increased, peaking at 60 MgDMha⁻¹ of dry matter (Bieleńska et al., 2015). According to Mbagwu and Piccolo (1990), the degradation of organic components in sludge significantly increases the accessibility of nutrients like nitrogen and phosphorus. The net nitrogen of soil particles increased by 57% and the amount of phosphorus by 64.2% after the amendment of SS at a dose of 200 Mt h⁻¹. The aerobic degradation of SS components produces both organic and inorganic acids, which raises the soil's acidity.

Urbaniak et al. (2017) reported that the addition of different doses of sludge caused a rapid and significant increase in soil enzymatic activities, soil biomass, soil respiration and CO₂. These increases were especially noticeable in soil treated with high doses of sludge. According to recent research, increasing the amount of composted sludge improved electrical conductivity, soil pH, aggregate stability, percentage of moisture of the dry soil at field capacity and wilting point, available P, and exchangeable K in soil systems (Curci et al., 2020). Adhering to local regulations and considering crop needs is crucial to prevent health risks, environmental pollution, and meet crop-specific requirements (Chang et al., 2001).

3.2. Long and short term application effects

The long-term impacts of sewage sludge on soil are less obvious and may vary depending on factors such as soil type, climate, and dose of sludge applied. According to certain research, long-term sewage sludge application can enhance soil microstructure and increase the presence of biopores (Simões-Mota et al., 2022). Other studies have found that heavy metals in sewage sludge can accumulate in soil over time and potentially affect soil microorganisms (Kinkle et al., 1987).

Limited studies have been conducted on the effects of short-term sewage sludge addition on soil properties, microbiological activity, and composition. It is vital to investigate the significant changes in bacterial composition and structure that occur with short-term utilize of sewage sludge in order to effectively integrate agronomic and economic gains with environmental issues. The previous study aimed to show that even short-term additions may significantly boost soil fertility, crop yields, and crop quality (Curci et al., 2020). While the application of sewage sludge over time can lead to the accumulation of contaminants. Notably, the long-term effects of sewage sludge use in saline–alkali should be evaluated on a case-by-case basis, considering specific site conditions, nutrient management planning for sludge application.

3.3. Soil types and climatic conditions

Sewage sludge application to agricultural land can be beneficial for various soil types, depending on their specific needs and conditions. In general, sandy soils can benefit from sewage sludge application as it improves water-holding capacity and nutrient retention. The organic matter and nutrients in the sludge can enhance fertility and overall soil health. Clay soils, with their higher water-holding capacity, may require more careful management when applying sewage sludge. The addition of organic matter from the sludge can help improve soil structure and drainage, but care should be taken to prevent compaction and avoid excessive nutrient buildup. Loam soils, being a balanced soil type, are generally well-suited for sewage sludge application. They have good water-holding capacity, drainage, and nutrient retention, allowing for effective utilization of the nutrients and organic matter in the sludge (Division, 2001; Meena et al., 2020; Singh et al., 2011). Regular soil testing and monitoring are recommended to assess nutrient levels and ensure that the application of sewage sludge is balanced and beneficial for the specific agricultural land. The carbon content of loamy-clay soil was enhanced from 0.16% to 1.45% by applying SS at a concentration of 60 t ha⁻¹ (Muter et al., 2022).

Consulting with agricultural extension services or soil scientists can provide valuable guidance on the appropriate use of sewage sludge for agricultural soil. The previous study found that the adoption of sewage sludge as an agricultural management strategy can improve soil properties and crop production. The research also investigate the quantity of composted sludge improved, soil pH (Curci et al., 2020). Another study revealed that organic matter input to sewage sludge modifies the physical and chemical properties of soils, and that this addition may considerably transform soil structure, increase soil moisture and porosity, and improve humus content and cation exchange capacity (Lloret et al., 2016). Soil tillage refers to the mechanical manipulation of soil, such as plowing or cultivation. It can affect soil structure, organic matter content, and nutrient availability, which in turn can influence the behavior of heavy metals and organic compounds in the soil (Singh, 2018). A recent study discovered that applying sewage sludge improves soil characteristics and rice production. The results demonstrated that applying sewage sludge improved soil fertility by lowering pH and increasing OC, nitrogen, and phosphorus content in salt-affected mudflat soil (Shan et al., 2021). According to these studies, sewage sludge consider to be beneficial to a variety of soil types. Further research is needed, to more understand the impacts of sewage sludge on the different types of soils.

Climatic conditions is also influences the soil moisture levels, evaporation rates, and plant growth, all of which influence the behavior and fate of heavy metals and organic compounds in the soil. Temperature, precipitation, and humidity are dominating weather patterns in the regions. Previous study showed that sewage sludge is an effective way to improve yield, yield parameters and metal content of barley under arid climatic conditions (Angin and Yaganoglu, 2012; Zoghalmi et al., 2020). Proper irrigation management can minimize runoff, leaching, and potential soil and groundwater contamination by heavy metals pathogens in sewage sludge (Singh and Agrawal, 2008).

3.4. Rain-fed and irrigated conditions

In both Rain-fed and irrigated conditions can have different effects on the behavior and impacts of sewage sludge when applied to soil. In rain-fed areas, the sewage sludge may get diluted and dispersed when rainfall occurs, which can help distribute the nutrients and organic matter more evenly in the soil (Yagmur et al., 2017). The heavy rainfall can lead to increased leaching of nutrients from the sludge and then nutrients may move below the root zone, potentially reaching groundwater or surface water bodies (Urbaniak et al., 2016). High-intensity rainfall can also cause soil erosion, resulted loss of applied sludge and associated nutrients.

Under irrigated conditions, the application of sewage sludge can have both benefits and potential challenges. Sewage sludge contains valuable nutrients when applied under irrigated conditions, these nutrients can be readily available to plants, promoting growth and productivity. Irrigation provides a controlled water supply, allowing for efficient water management and nutrient distribution (Shortle et al., 2001). This can help optimize the utilization of nutrients from the sewage sludge and reduce the risk of nutrient leaching (Levidow et al., 2014; Puy et al., 2021). The quality of the irrigation water is crucial when using sewage sludge such as heavy metals or pathogens, can pose risks (Sehler et al., 2019; Singh et al., 2021).

3.5. Greenhouses gases (GHG) emissions

Sewage sludge application can potentially contribute to the emission of GHGs, such as carbon dioxide (CO₂), methane (CH₄), and nitrous oxide (N₂O). These gases can influence the environmental impact and carbon footprint associated with sewage sludge application (Liu, 2018). The previous study suggests that using high application rates of hydrochar derived from activated sewage sludge and straw is preferable for soil amendment. Additionally, amending soil with hydrochar derived from sewage sludge shows promise in reducing greenhouse gas (GHG) emissions. These findings highlight the potential benefits of using hydrochar derived from sewage sludge as a sustainable soil amendment option, both for improving soil quality and mitigating GHG emissions (Joshi et al., 2022).

3.6. Nitrates (NO_3^-) leaching

Sewage sludge is rich in organic matter and nutrients, including nitrogen (N). When applied to soil, it can increase the overall N content and potentially lead to higher NO_3^- levels in the soil. This may increase the risk of NO_3^- leaching, thus the higher organic matter levels can reduce the risk of NO_3^- leaching by increasing the soil's ability to retain and immobilize nitrogen.

Furthermore, rate and timing of sewage sludge application can influence NO_3^- leaching. Applying sludge in excessive amounts or at inappropriate times, such as during heavy rainfall or in soils with high drainage rates, can increase the likelihood of NO_3^- leaching. The soil properties play significant role in NO_3^- leaching. To mitigate the risk of NO_3^- leaching from sewage sludge application, it is important to consider factors such as nutrient content, soil conditions, and application practices. Nitrate leaching can contribute to groundwater contamination and affect nutrient dynamics and the mobility of heavy metals and organic compounds in the soil (Shan et al., 2021).

3.7. Freezing–thawing cycles and wetting–drying

The effect of freezing–thawing cycles and wetting–drying processes on sewage sludge can have significant effects on its physical characteristics and potential environmental consequences.

Freezing–Thawing Cycles: When sewage sludge freezes and thaws, physical changes occur that alter its structure and behavior (Sahin et al., 2008). Because of the expansion and contraction associated with freezing and thawing, sludge particles might break apart, resulting in increased surface area and the possible release of stored water and gases (Risk et al., 2013). This can have an impact on the moisture content, porosity, and the permeability of sludge. Additionally, freezing–thawing cycles can impact the biological activity in the sludge (Shekarrizfard, 2012). Microorganisms present in the sludge may be affected by the extreme temperature changes, leading to changes in their activity levels and potentially impacting the sludge's decomposition and stabilization processes (Semblante et al., 2015). Recent findings suggest that applying a high dose of sewage sludge can effectively improve clay soil. This approach is particularly useful in areas with frequent wetting–drying cycles and freezing–thawing conditions associated with wastewater (Badaou et al., 2022).

Wetting–Drying Processes: Wetting and drying of sewage sludge can also have notable effects, when sludge dries out, its moisture content decreases, leading to shrinkage and compaction. This can result in changes in the sludge's physical structure, such as increased bulk density and reduced porosity (Sänger et al., 2001). Dry SS typically comprises 30%–50% mineral constituents and about 50–70% organic content (Muter et al., 2022; Siwal et al., 2022). When agricultural soils are treated with the organic enriched SS, their physical, chemical, and biological properties can be significantly enhanced. Particularly, a decreased bulk density results in better soil structure, water-retaining capacity, and improved soil porosity. Additionally, when the sludge gets wet, it absorbs water, potentially leading to reduced water infiltration and drainage, this can affect the sludge's permeability, Ahmed et al. (2019) and Grüter et al. (1990). Both wetting and drying processes can also influence the release of nutrients and contaminants from the sludge. When sludge dries out, it may release airborne particles, including dust, which can contain contaminants or pathogens. When the sludge becomes wet again, there is a possibility of nutrient and pollutant leaching into the surrounding environment if proper management practices are not in place.

It is important to consider these processes and their potential impacts when managing sewage sludge. Proper storage, handling, and application practices should be followed to minimize the risks associated with freezing–thawing cycles and wetting–drying processes. This may include covering the sludge to protect it from extreme weather conditions, avoiding direct contact with water bodies, and implementing appropriate measures to prevent nutrient and contaminant runoff during wet periods (Badaou et al., 2022).

4. Effects of sewage sludge on saline–alkali soil, crop, and groundwater

4.1. Effects of sewage sludge in saline–alkali soil

Saline–alkali soil is a result of both natural and man-made influences (Yuan-xiu et al., 2001). Soil salinization caused by human factors by excessive irrigation with saline water, overuse of synthetic fertilizers, blind reclamation, excessive logging, overgrazing, unreasonable construction, and other activities. The wastewater drainage may lead to groundwater, the groundwater level will rise, and the salt will remain on the surface due to the evaporation of water, resulting in salt accumulation in the soil. Soluble salts, primarily Na^+ , Ca^{2+} , Mg^{2+} , SO_4^{2-} and secondarily K^+ , HCO_3^- , NO_3^- , and B, can affect saline–alkali soil.

The efficacy of different organic supplements, such as compost made from municipal solid waste (MSW) or sewage sludge, has been examined for remediating saline soil, both amendments increased soil carbon and nitrogen levels, consistent with the observations of studies (Tejada et al., 2006; Walker and Bernal, 2008).

Sewage sludge is a valuable raw material for agriculture because it is high in organic matter, phosphorus, nitrogen, and other micro and macro elements. The high salt content in sewage sludge can limit its use in agriculture because it can increase soil salinity levels (Wei et al., 2019). However, some studies have shown that composted sewage sludge can

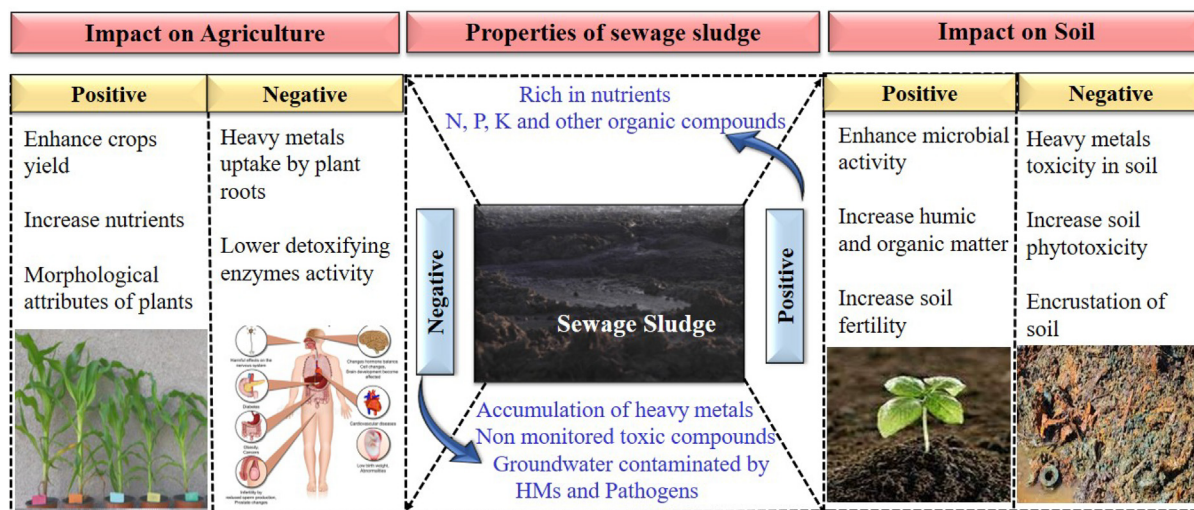


Fig. 3. Positive and negative sides of SS on soil and agricultural production.

be used as fertilizer in agriculture. During composting, straw, wood chips, bark, tree leaves, potassium fertilizer, and lime are added as amending and/or bulking agents to improve the fertility of composted sludge (Zhihong, 1998). The use of sewage sludge in agriculture can affect the salt content and pH of the soil. Sewage sludge contains various organic and inorganic compounds, including nutrients and salts. When sewage sludge is applied to soil, it can increase the salt content, specifically the concentration of ions such as sodium, chloride, and others.

To reduce the salt content in soil when using sewage sludge can be implemented:

- **Dilution:** Mixing the sewage sludge with other soil amendments or organic matter can help dilute the salt concentration. This can be done by incorporating compost, manure, or other organic materials into the soil along with the sewage sludge (Alvarenga et al., 2015). Regarding the pH of the soil, sewage sludge tends to have a high pH due to its alkaline nature. This can be attributed to the presence of calcium compounds and other alkaline substances in the sludge. To neutralize the pH and make it suitable for agriculture, several approaches can be employed:
- **Acidification:** Adding acidic materials such as sulfur or elemental sulfur to the soil can help lower the pH. This process is known as soil acidification and should be done carefully, taking into account specific soil requirements and crop preferences (Wei et al., 2019).
- **Liming:** If the soil is highly acidic, applying lime (calcium carbonate or other liming materials) can help raise the pH to a more neutral level. However, attention should be consider to prevent excessive liming as it can lead to an overly alkaline pH (Pagani and Mallarino, 2012).

Sludge properties change the soil's properties, which may impact metals' and other nutrients biogeochemical behavior (mobility and bioavailability). As a result, changes in soil quality induced by SS usage could have a major impact (Badaou and Sahin, 2022). Consequently, SS for crop irrigation in the agricultural sector has the possibility impact to soil quality/productivity, crop production in both positive and negative ways, as illustrated in Fig. 3. Pathogens and chemical substances in SS may pose health and environmental risks (Lewis and Gattie, 2002; Wang and Wang, 2007). Crop irrigation using wastewater has negative implications owing to the high concentrations of total suspended and dissolved particles, nutrients, and potential toxics elements (PTEs) (Li et al., 2017; Rattan et al., 2005). Salt concentrations in SS can degrade the quality of soil and output by accumulating in the root zone (Goldan et al., 2022). The long term use of saline and sodium-rich wastewater can have harmful effects on soil structure and productivity over time. The presence of HMs, which are well-known to have a negative impact on agricultural productivity, accounts for the significant effect of SS on crop yield (Li et al., 2017; Rattan et al., 2005). Sludge nutrients can degrade soil structure or restrict plant development near the dumping site, causing groundwater pollution through infiltration or surface water contamination through runoff (Goldan et al., 2022; Kirchmann et al., 2017).

The soil pH is the critical variable that governs metal partitioning between the solid and solution phases of soil. The pH of soil influences the adsorption/desorption of PTEs and, as a result, their biogeochemical behavior in the soil-plant system (Moolenaar and Beltrami, 1998; Palansooriya et al., 2020). There is a negative association between soil pH and PTE bioavailability in plants for several PTEs (Shahid et al., 2018). Due to the enhanced availability of most nutrients, most vegetables grow best on soils with a pH between 6.0 and 7.5. The influence of sludge on soil pH is complicated; in most investigations, soil pH increased considerably following long-term irrigation with sludge from various wastewater

treatment plant sources. (Hassanli et al., 2008; Kunhikrishnan et al., 2012). Yet, in other research, long-term SS did not affect soil pH (Christou et al., 2014), while others observed decreasing soil pH (Rattan et al., 2005). The pH of the sludge and the soil's pH buffering capacity dictates the sludge's impact on soil pH. Changes in the equilibrium of complex dynamic processes occurring in the soil simultaneously can alter soil pH. Previous studies (Badaou and Sahin, 2022; Sousa et al., 2011; Tandi et al., 2004) on SS usage enhanced soil pH, whereas other research observed pH declines (Delibacak et al., 2020; Hornick et al., 1984; Iticescu et al., 2021; Stabnikova et al., 2005). The formation of H^+ ions induces the decrease in soil pH during oxidation processes, and it may also be caused by the neutralization of H^+ ions in sludge by calcium carbonate. As a result, the total effect on soil pH is influenced by the baseline soil pH, as well as the cation/anion ratio and sludge chemistry.

Similarly, soil organic matter (SOM) is important in assessing soil quality, the SOM influences the soil–plant system's metal and nutrient biogeochemical behavior (mobility/bioavailability) (Orlov and Sadovnikova, 2005). The organic matter mostly determines the processes that influence metal behavior in soil. SOM is stated to be suspended or dissolved in an aqueous media. Mehmood et al. (2017). As a result, SOM has the potential to significantly affect (increase or decrease) the mobility of PTEs in soils and their availability to plants (Huang et al., 2017; Shahid et al., 2017). Organic matter (OM) also provides essential nutrients for plant development (Muter et al., 2022). SOM content is also required for soil microbial activity regulation. Due to aeration concerns in the soil, high OM inputs increase microbial proliferation while closing soil pores, limiting soil penetration, and promoting anaerobic microbiological growth (Bot and Benites, 2005; Usharani et al., 2019). Applying SS may enhance the OM content of the soil, which is thought to be helpful to soil (Bot and Benites, 2005). The soil's structure is improved, its capacity for cation exchange is boosted, it helps retain metals by decreasing their bioavailability and mobility, and it feeds the soil with nutrients by adding organic matter through wastewater application (Bot and Benites, 2005; Usharani et al., 2019). Yet, wastewater application might result in greater organic matter concentrations that can negatively affect the soil's porosity and lead to anaerobic conditions in the root zone (Singh and Kalamdhad, 2011). Also, if a larger OM content in agricultural runoff enters groundwater, it might cause the water's dissolved oxygen to drop, leading to hypoxic conditions and a rise in the death of aquatic species.

Moreover, adding high carbon content containing organic matter may help mitigate the “salting-out” process associated with the decline in enzyme solubility by altering the enzyme's catalytic site. Furthermore, (Rasul et al., 2006) predicted that these microbes would probably have poor substrate use efficiency. Thus, microorganisms could combat the short-term effects of salt stress by directing the consumption of organic substrates to continue a metabolic activity (Evelin et al., 2019). It has been demonstrated that adding sludge to the soil as a soil amendment increases the activity of soil enzymes such as arylsulfatase, acid phosphatase, and alkali phosphatase. Increasing SS dosage, basal respiration, and fluorescein diacetate hydrolysis efficiency increased (Vieira and Pazianotto, 2016). Alterations in urease activity by soil microorganisms can be covered in two aspects. First, urease activity indicates the behavior of microorganisms engaged in the soil nitrogen cycle (Marschner et al., 2003). Another factor is the worldwide loss of nitrogen, about 70% caused by urease activity if urea is used as a fertilizer. To sustain soil fertility, urease suppression is used worldwide (Modolo et al., 2018).

4.2. Effects of sewage sludge on crop production

The distinctiveness of SS is found in its multi-mineral composition and a wide variety of organic matter. SS comprises nitrogen–phosphorus–potassium organic fertilizer containing all the micro elements required for crop growth (Bai et al., 2017). Improving crop yield, as well as the deposition of nutrients and organic materials in the soil, can be accomplished by amending the soil with SS. However, if the SS is consistently utilized, it is necessary to regularly monitor the concentration of humic substances in soil and plant tissue (Eid et al., 2020). After pyrolysis, SS could potentially be utilized as fertilizers. The single treatment of SS and the corresponding biochars provided sufficient P for the plants to produce higher biomass than traditional P-fertilizers (Rehman et al., 2018). Depending on its application, SS affects plant growth differently, such as “mulching” at the soil's surface or mixing it evenly with the soil. Using SS on the substrate has certain benefits, including limiting water evaporation by creating a physical barrier that prolongs soil moisture retention. These enhanced the biological and chemical activities involved in transforming organic matter (Boudjabi and Chenchouni, 2021). One of the studies noted that the best wheat production was attained when dried SS is applied at the surface of clayey–silty soil (mulching) compared to when SS was mixed with soil homogeneously. Incubation experiments were carried out with the dewatered sludge from municipal sewage applied to highly saline alkali soil in various concentrations. Sludge-amended saline–alkali soil's physical and chemical characteristics and changes over time were investigated. Results revealed that the bulk density of soil, pH, and sodium percentage exchange was significantly lowered.

In contrast, soil nutritional contents increased significantly, and the hazard potential from HMs in the amended soil was reduced during 20 months. A good sludge dose was determined using wheat germination and growth as a diagnostic indicator. It was revealed that sludge accounted 30% to 50% of the weight of mixed soil (Meng et al., 2014). Research showed that using SS with mineral fertilizers positively impacted maize productivity and soil microbial activity. Additionally, studies involving cucumbers and leaf mustard have been conducted. The combination of SS preparation with nitrogen-enriched fertilizers considerably increased plant growth and increased plant development, but SS preparation solely did not supply the plants with suitable amounts of mineral nutrients. The nutrition of plant minerals may benefit over the long term as a result. Additionally, our results revealed that various plants respond to SS in various ways (Dubova et al., 2020). A species-specific effect, in that scenario, can be described by (i) different susceptibility of plants to the

Table 5
Utilization of sewage sludge for crop productivity and their effects.

Dose	Crops	Effects	References
40 t ha ⁻¹	Wheat	Increase grain yield	Jamil et al. (2004)
80 t ha ⁻¹		Increase straw yield	
5 t ha ⁻¹	Cabbage	Increase head and stump	Mathakiya and Meisheri (2007)
25 t ha ⁻¹	Radish	Yield increased	Lima et al. (2016)
42, 58 and 77 tons ha ⁻¹	Cotton	Increase yield	Samaras and Kallianou (2000)
10 Mg ha ⁻¹	Cotton	Increase nutrient uptake and yield along with soil properties improvement	Samaras et al. (2008)
30 t ha ⁻¹	Sunflower	Improved yield production	Albuquerque et al. (2015)
33 kg ha ⁻¹ urea and 20, 30, and 40 t dry sludge ha ⁻¹	Wheat	higher grain and straw yield attributes	Tamrabet et al. (2009)
120 and 240 kg N ha ⁻¹ in sewage sludge	Maize	yields increased	Černý et al. (2012)
300 t ha ⁻¹	Rye grass	Increased biomass of roots and aboveground plant parts	Gu et al. (2013)
sewage sludge	Maize and Barley	A sufficient increase in yields	Hernández et al. (1991)
20 t ha ⁻¹ , 40 t ha ⁻¹ , 30 t ha ⁻¹	Rice and Wheat	Enhanced rice grain and wheat straw yield	Özyazici (2013)
SS and 50% NPK	Beta vulgaris	Increase production	Roy et al. (2013)
80 t ha ⁻¹	Lettuce	Increase head yield	Sönmez et al. (2006)
40 t ha ⁻¹	Rice	Improved grain production	Latare et al. (2014)
60 Mg dry weight S.S ha ⁻¹	Winter wheat	higher grain weight and yield	Koutroubas et al. (2014)
250 t ha ⁻¹	Sweet Sorghum	Biomass increased	Zuo et al. (2019)
12 t ha ⁻¹	Wheat and Barley	increased test weight, height, number of tillers, and grain yield	Outhman and Firdous (2016)
SS (30 g kg ⁻¹)+Thiourea (6.5 mM)	Wheat	Improved growth attributes	Mansoor et al. (2021)

constituents in SS preparations; (ii) requirement for mineral components during the early periods of ontogenesis owing to a slower release of minerals from SS; (iii) inadequate maturation and the prevalence of growth inhibitors within SS (Muter et al., 2022). SS is employed in all developed and developing countries as an effective organic fertilizer. Table 5 lists the crop responses to the application of sludge.

4.3. Effects of sewage sludge on groundwater

Water is main resource for human life, but the presence of pathogens, chemical and microbial contamination in groundwater threaten its quality (Dilpazeer et al., 2023; Jat Baloch et al., 2023, 2020, 2022b; Li et al., 2023; Tariq et al., 2022; Zhang et al., 2022a). Thus the contaminated groundwater has been linked to various health problems. The interval between applying SS to the soil and making management measures to safeguard groundwater quality is crucial to consider (Barber et al., 1988; Li et al., 2017; Mora et al., 2022; Rattan et al., 2005). A widespread technique that increases crop yield and boosts climate resilience owing to the use of SS for irrigation (Muamar et al., 2014). Unfortunately, In areas where wastewater is irrigated intensively and over an extended period, this activity degrades the quality of the groundwater, potentially endangering both human health and ecological security (Akram et al., 2020b; Iqbal et al., 2021; Jat Baloch and Mangi, 2019; Jat Baloch et al., 2021, 2022b; Rattan et al., 2005; Talpur et al., 2020). The salinization of groundwater is one of the most detrimental effects, describing the primary mechanisms involved in the movement of certain pollutants from the topsoil to the saturated zone (Modi et al., 2022). This approach causes significant salt accumulation in soils and groundwater due to SS (Zuo et al., 2022). These salts leak beyond the vadose zone and root zones, contaminating the aquifers and changing the chemistry of the groundwater (Akram et al., 2020a; Pulido-Bosch et al., 2018). Zones with high total dissolved solids (TDS) concentrations in the groundwater might eventually reach levels of long-term SS (Akram et al., 2021; Rattan et al., 2005; Zuo et al., 2022). Due to the buildup of salt content, more specifically sodium chloride, groundwater becomes more saline because of the accumulation of sodium and chloride ions (Iqbal et al., 2023; Jat Baloch et al., 2022a; Zhang et al., 2022b). The alkali and salinity might cause the type of groundwater to change from Ca²⁺-Mg²⁺-HCO₃⁻ to Na⁺Cl⁻. Furthermore, high alkali conditions may degrade the soil structure and impair plant development in integrated systems when groundwater is used for irrigation (Rattan et al., 2005).

Thus, based on salinity and alkali criteria, water classification methods have been devised to limit water use for irrigation. Also, the SS would be properly treated before being used on the soil, perhaps preventing groundwater contamination (Rattan et al., 2005). HMs in sludge may collect in the topsoil and subsoil layers of sludge farming sites because the positive metal ions immensely attract the negative hydroxyl groups of organic matter and clays (Badaou and Sahin, 2022; Zuo et al., 2022). Recent studies have shown that elements like As, Cd²⁺, Cr²⁺, and Pb²⁺ can travel to deep soils in regions exposed to long-term pollution, where they can then reach and contaminate shallow aquifers (Yang et al., 2021). This could be brought on by the soil systems being more salinized since increasing soil salinity may allow metals like Cd²⁺, Hg²⁺, and Pb²⁺ to leach from sludge farming soils into groundwater. Even though several

metals can permeate the soil column, their infiltration into aquifers may be influenced by a variety of variables, including soil chemistry and grain size, low unsaturated zone thickness values (water tables typically lower than 8 m), and the hydrogeological structure of aquifers (Yadav et al., 2015).

5. Sewage sludge as a source of heavy metal pollution: Effect on agriculture sector

Heavy metals in SS can be found in the form of dissolved, precipitated, adsorbed, or linked to solid particles there is limits set for HMs in SS approved for agricultural purposes (Bianchini et al., 2016; Hernández et al., 1991; Mininni et al., 2015). Raw sewage's source is the only factor determining the number of HMs found in industrial wastewater are Zn^{2+} , Cr^{2+} , Cd^{2+} , Pb^{2+} , Cu^{2+} , As, Hg^{2+} , and Ni^{2+} (Olujimi et al., 2012). SS utilized for agricultural purposes is contaminated with HMs due to toxic metals in raw sewage (Gao et al., 2015). Industrial wastewater and soil surface runoffs are the main sources of HMs in SS (Fijalkowski et al., 2017; García-Gil et al., 2004; Korboulewsky et al., 2002). Although the concentration of HMs in SS infrequently exceeds the legal limit, a protracted accumulation of these substances in the sites where SS is disposed of can be extremely hazardous to the environment (Iglesias et al., 2018). Heavy metal concentrations in soil are raised using excessive quantities of manure, industrial wastes, sewage sludge, and toxic agricultural chemicals (Kelepertzis, 2014). According to studies, they were utilizing SS as fertilizer results in higher soil concentrations of HMs (Marguí et al., 2016). Although if toxic metals are found in soil at very low concentrations, roots can easily absorb them and deposit them in edible plant portions (Jolly et al., 2013). (Shi et al., 2016) documented that the absorption of HMs through soil varied in different wheat plant parts; it was found that Cu^{2+} , and Ni^{2+} concentrations were the highest. According to Hu et al. (2013), supermarket-purchased vegetables contained Pb^{2+} (16%), Cd^{2+} (26%), and Cr^{2+} (0.56%) contamination. Depending on the concentration levels of the recognized HMs, the abundance above sequence was suggested: $\text{Cr}^{2+} > \text{Zn}^{2+} > \text{Ni}^{2+} > \text{Cd}^{2+} > \text{Mn}^{2+} > \text{Pb}^{2+} > \text{Cu}^{2+} > \text{Fe}^{2+}$. The Ni^{2+} , Pb^{2+} , Cd^{2+} , and Cr^{2+} levels were 90%, 28%, 83%, and 63% higher than the World Health Organization's threshold limits (Balkhair and Ashraf, 2016). HMs create selective pressure on microorganisms, encouraging the growth and spreading microbial resistance to such contaminants (Menz et al., 2018).

HMs pose a serious health concern to animals and humans because they can concentrate in SS and spread to crops and soil water (Gul et al., 2015; Korboulewsky et al., 2002). However, the impact of SS as fertilizer on soil has not yet been thoroughly studied. Extensive research is required, as microorganisms confronted with toxic HMs quickly acquire resistance to many antibiotic drugs. Therefore, application of SS can potentially enhance metal concentrations in plant parts. This enhancement can generate disorganization at the cell and organ levels, such as disruption in mitochondria and chloroplast Fig. 4. As stated by one study, urban sewage use is safe, especially in the short and medium term. However, industrial sludge was found to have the most negative consequences (Lassoued and Essaid, 2022). Heavy metal contamination has emerged as the main barrier to applying SS in agriculture (Liu and Sun, 2013). Plants play a crucial role in the speciation and availability of HMs in soil, particularly when sludge is used as a nutrient source. Metal-chelating substances and metal-reducing proteases found in plant root exudates impact heavy metal diversification. Plant roots discharge protons, contributing to the acidification of the rhizosphere soil and increasing the acid-soluble component. Soil microorganisms and their community composition also influence heavy metal availability. Different plants produce distinct types and amounts of exudates, affecting soil microbes in unique ways. The concentration of HMs in the rhizosphere and non-rhizosphere differs as a result of the combined interaction of the aforesaid factors (Sivapatham et al., 2014; Su et al., 2004). Importantly, it is not suggested to apply SS directly to agricultural soils. It was demonstrated that the SS that had undergone hygienic treatment by liming retard the white mustard growth at a proportion of 10%. Sludge's phytotoxicity was reduced in all measured ratios, ranging from 5 to 50%, by adding compost (5%, 15%, and 25%) (Šindelá et al., 2020). Therefore, it is essential to maintain and enhance localized implementation of sewage sludge, either to improve and restore deteriorated soils or to assist the phytoremediation process of contaminated soils, integrating the accessibility of these wasted bio-resources with the evaluation of their ability to improve agro system sustainability. It is important to balance the benefits and drawbacks of using these bio resources.

5.1. Immobilization of toxic metals

Two techniques are available to reduce the pollution caused by HMs in sewage sludge: removal and immobilization. The first step eliminates the pollution hazard posed by HMs by removing them from SS via chemical leaching, bioleaching, electrochemistry, or a combination of these methods. The cost of immobilizing harmful metals from sludge is higher than the cost of removing HMs from sludge. The heavy metal contaminants removed from SS should be carefully considered to prevent secondary pollution. The second step converts HMs into relatively stable components, lowering their permeability and bioavailability (He et al., 2015). The two most often utilized immobilization techniques are composting of SS and chemical immobilization. Composting is a complicated dynamic digestive process with three main phases: mesophilic, thermophilic, and cooling phase (Bernal et al., 2009). The most often used chemical immobilizing agents are aluminosilicate, phosphorus-based minerals, essential compounds, and sulfides. Removing toxic pollutants from SS can be accomplished through chemical immobilization or composting. Composting or chemical additives would alter environmental properties over time. For instance, phosphoric acid helps in lowers the pH of sewage sludge, enhancing the leaching chances of various metals. The two main issues that must be resolved are enhancing the fixing impact of HMs and assuring their long-term stability.

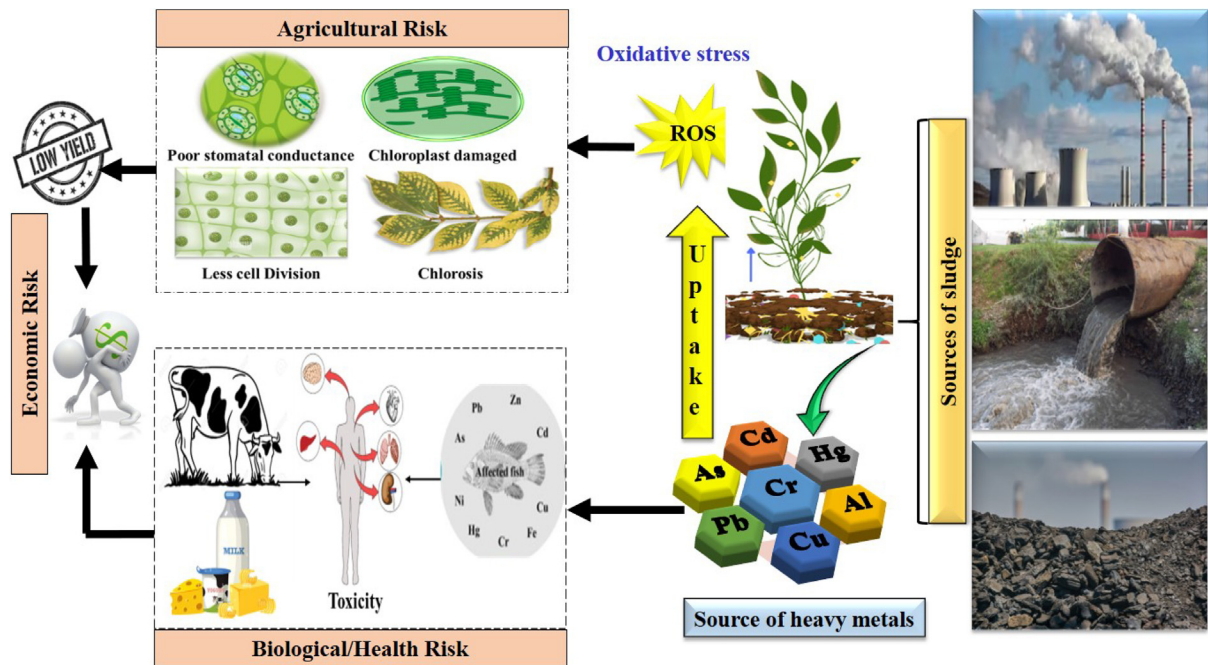


Fig. 4. Sewage sludge as a source of heavy metals in agriculture.

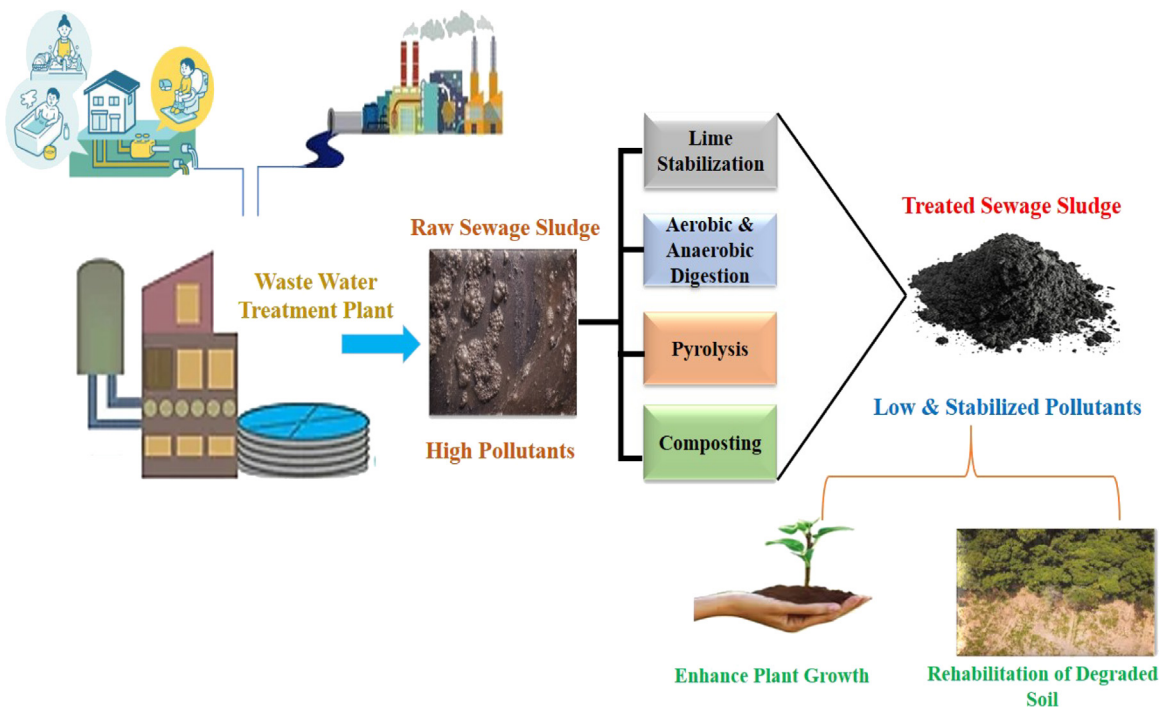


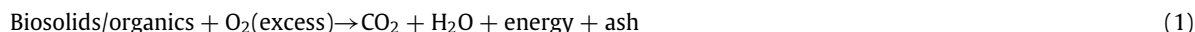
Fig. 5. Treatment techniques of sewage sludge for the crop production.

6. Innovative treatment techniques to improve sewage sludge use efficiency

Many types of sewage sludge treatment strategies have been implemented for crop production in order to accomplish the treatment effects of sludge stability and harmlessness as shown in Fig. 5. However, due to the vast scale of sludge disposal, high treatment costs of existing technologies, and low safe disposal rate (Cieřlik et al., 2015; Mustapha et al.,

2017), the current economic treatment technology and scientific utilization mode of sludge need to be further investigated. Moreover, sludge's material/nutrient levels vary due to the diversity of sources (Tyagi and Lo, 2013), and sludge may contain toxic and harmful substances such as HMs, pathogenic microorganisms, antibiotics and resistance genes (Chen et al., 2012; Kelessidis and Stasinakis, 2012; Muamar et al., 2014). Sludge can negatively affect soil health, crop growth, groundwater, biodiversity, and human health if it is used without proper treatment (Li et al., 2017; Mora et al., 2022). It is found that 70%~90% of HMs (Zn^{2+} , Cu^{2+} , Ni^{2+} , Cd^{2+} , Pb^{2+} , etc.) are transferred to sludge through adsorption or sedimentation during sewage treatment, which can increase the content of HMs in soil and crops to varying degrees posing a potential threat to ecological or food security and human health (García-Gil et al., 2004; Zuo et al., 2022). Firstly, the regulation of key components of sludge and their impact on crops, water, and soil environment is one of the difficulties in this technical breakthrough. Based on the preliminary work, combined with biotechnology and nanotechnology, the microecological regulation of water and soil environment and the simultaneous removal and absorption of risk factors and nutrient elements in sludge farming.

The exothermic oxidation of biosolids during incineration produces ash, CO_2 , and H_2O , as well as a small quantity of heat Eq. (1). Although 90% less sludge is produced when burned, and pathogens are eliminated. About 30% of the ash left over can be used to make building materials, or used in crop production. Due to the limited use of WAS on arable land for food production (Peccia and Westerhoff, 2015), the incineration of WAS has recently attracted much interest in some countries (Adam and Krüger, 2014). But the increased concentrations of HMs and the restricted access to phosphorus by plants are often linked to incineration (Adam and Krüger, 2014). So, many strategies are being explored to either enhance the incineration ashes or directly recirculate WAS-P. Previous studies provide an overview of the operational parameters and outcomes of numerous novel techniques, including acid leaching (Xu et al., 2012a), electrodialysis (Viader et al., 2015), and the process of thermal treatment using polyvinyl chloride (PVC) and magnesium oxide (MgO) (Vogel et al., 2013). Thomsen et al. (2017) indicated that sludge is an effective and valuable source of P fertilizer for agricultural systems because of the high quantity of total P retained in char and ash and the reduced HMs per unit of P. The recovery of energy in the form of heat or electricity via WAS incineration methods has become more prevalent recently (Gorgec et al., 2016; Thorpe et al., 2017).



Fluidized bed (FD) incinerators have been deemed to be well effective for burning WAS in the form of dry or wet phase (with approximately 35–59 wt% moisture content) due to their high combustion efficiency (e.g., lower organic fraction in the fly ashes, 0.3%) and very low pollution generation Sulfur oxides (SO_x) and Nitrogen oxides (NO_x) 200 mg Nm^{-3} (Fytli and Zabaniotou, 2008). In Murakami et al. (2009), successfully demonstrated the combustion of WAS in a special FD incinerator (capacity: 4.32 t day^{-1}) (Murakami et al., 2009). Less than half of the CO_2 , NO_x , and nitrous oxide (N_2O) emissions measured in the flue gases were compared to conventional plants. An incineration facility with a daily capacity of 100 tons can save 50% on energy, over 40% on CO_2 emissions, and \$200,000 on fuel and energy expenses. The metro WWTP in St. Paul, Minnesota has successfully deployed an incineration technology with a 4.7 MWe energy-generating capacity, resulting in annual savings of around \$1 million and a 20% reduction in greenhouse gases (GHG) emissions, according to the National Association of Clean Water Agencies (NACWA) (Anderson et al., 2016). Another instance of effective use of this technique is the Vassiliko cement mill in Cyprus (Jorge and Dinis, 2013).

The following summarizes the benefits of WAS co-incineration in coal-fired power plants (Hong et al., 2013).

- (i) To avoid the high expense of incinerator technology;
- (ii) To decrease GHG emissions;
- (iii) To improve energy retrieval's effectiveness and increase public acceptance.

Additionally, low-caloric excess heat from exhaust gases emitted by power plants may successfully improve the sludge drying process (Rulkens, 2008). So, more research needs to be done on the co-incineration of WAS with other feedstocks (like coal, wood, etc.), the design of energy-efficient incinerators, and the improved and optimized management of ashes so that energy can be used and nutrients can be recovered at the same time.

Pyrolysis is the heat conversion of WAS (350–900 °C) in an oxygen-deficient atmosphere, producing vapors or pyrolytic gases. The vapors must be condensed by cooling to separate the liquid or oil, leaving char as a solid byproduct (Tian et al., 2013). These factors influence the process parameters, such as operating temperature, reaction time, pressure, and WAS properties, as well as the amount and quality of the liquid, gas, and char products all these factors are the key parameters determining the pyrolysis process. Slow pyrolysis is characterized by lower HR (0.1–1 °C s^{-1}), lower operating temperatures (300–400 °C), and longer GRT (5–30 min). In contrast, fast pyrolysis involves higher HR (10–200 °C s^{-1}), higher temperatures (450–600 °C), and shorter GRT (0.1–0.3 s^{-1}). Fast pyrolysis is a suitable approach for converting WAS into liquid or gaseous products. Advanced applied approaches to produce renewable fuel (bio-oil) by the pyrolysis of WAS include the Carver–Greenfield technology (C–GT), the Oil-from-Sludge technology (OFS), and the Siemens Schwell–Brenna Technology (SSBT) (Manara and Zabaniotou, 2012).

C–GT produces important products, including oil, animal feed, and fertilizer, via the multi-effect dehydration of water-bearing, WAS, and centrifugation (Ni et al., 2017). The generation of straight-chain hydrocarbons, which are later condensed into oil, is improved by OFS-based pyrolysis at 450 °C for more than 30 min under atmospheric pressure (Manara and Zabaniotou, 2012). Co-pyrolysis of WAS and crushed wastes at 450 °C in a rotating kiln is a part of SSBT (Werle and Wilk, 2010). The outcomes of WAS pyrolysis were performed using several techniques, including slow

pyrolysis (Gao et al., 2017), rapid pyrolysis (Atienza-Martínez et al., 2017), and microwave-aided pyrolysis (Raheem et al., 2018). Because different processes, operational settings, and raw materials are used, there are observable differences in the product properties and dispersion of WAS pyrolysis (Atienza-Martínez et al., 2017) when pretreatment (Torrefaction) and post-treatment (catalytic) were tested, reported a maximum liquid yield for anaerobically digested and thermally dried WAS rapid pyrolysis (32%) at 275 °C in FD reactor. (Raheem et al., 2018) recorded 46.14% of the maximum tar production at 550 °C. The low working temperatures of WAS pyrolysis prevent the HMs from melting and evaporating, which is one advantage (Leijenhörst et al., 2016). WAS pyrolysis primarily produces substantial volumes of char (about 50% of the bulk of sludge). These chars could be used to absorb HMs or other organic pollutants (Khan et al., 2019), or they could be used as a solid fuel source for heating. Pyrolysis char derived from WAS has been studied as a potential catalyst, catalytic support, and soil conditioner due to its low cost. Nevertheless, the potential risks associated with the behavior of HMs in pyrolysis char present concerns that need to be addressed before its utilization or disposal. In response, numerous recent studies have concentrated on investigating the distribution of HMs within pyrolysis char and bio-oil obtained from dried WAS (Gao et al., 2017). Most HMs were found retained in the char, while only a small amount was present in the bio-oil, regardless of the pyrolysis temperature used (Trinh et al., 2013).

Additionally, the bulk of the HMs that accumulated in the char at 600 °C significantly decreased in bioavailability, suggesting minimal environmental risk or eco-toxicity associated with the exposure of the char to the environment (Raheem et al., 2018). However, it may be strongly supported by increasing oil yields and making high-value products from char produced during pyrolysis. Oil, gas, and char are among the byproducts of WAS that may be used as raw materials to make biofuels and chemicals, among other things, such as used as bio fertilizers. Compared to other technologies, pyrolysis was shown to be a zero-waste process, potentially providing a remedy for the pollution associated with WWT. Overall, it can be concluded that the pyrolysis technique for WAS can address both economic and social problems and environmental standards for sustainable development (Samolada and Zabaniotou, 2014; Wang et al., 2016). To increase bio-oil production and immobilize or minimize the transfer of HMs to the products, it is necessary to implement more efficient strategies (based on the type and content of HMs in the WAS). These strategies include pre- and post-treatment, sorbents, and temperature optimization of pyrolysis.

6.1. General treatment

The presence of high levels of hazardous pollutants in soils can have detrimental effects on the soil ecology, impacting various soil characteristics such as pH, electrical conductivity, cation exchange capacity, soil mineralogy, and microbiological activity (Kabata-Pendias, 2011). Therefore, it is crucial to concentrate on introducing soil remediation strategies to ensure continuous soil usage, particularly because soils affected by industrial activities frequently sustain a sparse natural plant cover because of unfavorable growth circumstances caused by elevated accumulation and availability of HMs (Burgess et al., 2018; Zou et al., 2018). In addition, reestablishing plant cover on polluted soils is a crucial step against environmental pollution (Mahar et al., 2016). Numerous traditional methods available for the removing HMs from the environment, these include soil washing, drain and treat, flushing, electrokinetic remediation, stabilization, solidification, vitrification, permeable reactive barriers, and regulated natural attenuation (Sharma and Reddy, 2004). Although, most conventional methods for achieving cleanup levels require physically removing HMs from the soil environment, which have major secondary environmental effects and consume a lot of energy. Therefore, there is an important need to develop more environment-friendly remediation methods for polluted areas (Song et al., 2019).

6.2. Nano-biotechnological interventions for reclamation of sewage sludge-treated

Nanotechnology is very convenient, economic and environment friendly therefore it is gaining attention day by day over other conventional ways. The field of agriculture is observing an increasing trend towards the adoption of this technology, scientists are trying to design nanoparticles for agricultural applications on nanoplatforms (Asghar et al., 2018; Jiang et al., 2022). There are physical and chemical methods are used to synthesize the nanomaterials but it involves the utilization of forces and hazardous chemical reactions, which results in the degradation of nature (Javed et al., 2021). To overcome this environmental issue as well as the most economic, convenient, environment friendly and cost effective way is the green synthesis. The synthesis of nanomaterials through plant-mediated methods offers advantages over traditional physical and chemical synthesis approaches and these methods are biocompatible and provide viable alternative to conventional fertilizers, playing a significant role in agricultural applications (Jiang et al., 2022). The use of nanoparticles are cost effective method for synergistically enhance the efficiency of sewage sludge as compared to other methods (Yuan and Dai, 2017). This innovation introduces novel materials that present unique and valuable solutions to address the limitations of conventional materials, resulting in a wide range of applications (Khan, 2012). Nanomaterials have 1–100 nm nanoscale dimensions and often show novel and more significantly improved biological, physical, and chemical properties because of their nano-sized structure, increased surface area to volume, and quantum effects (Theron et al., 2008). In the past several years, there have been notable advancements in nanotechnology for treating and purifying water (Masciangioli and Zhang, 2003). Therefore, it is essential to evaluate the level of science of nanotechnology, which can enhance the quality of contaminated soil and restore degraded soil, and to investigate the feasibility of utilizing nano-enhanced materials in substitution of traditional amendments in agriculture. The specific

applications of nanotechnology being pursued include improving soil pH and fertility, enhancing soil physical properties, minimizing HMs toxicity, mobility and availability, and other toxic contaminants, stabilizing soil components and reducing soil erosion at different mining sites. This work aims to review the existing literature on numerous environment-friendly Nano-based materials that could be employed as soil amendments for soil reclamation of alkali saline soil treated with sewage sludge (Yuan and Dai, 2017).

According to Liu and Lal (2012), some nanomaterials with significant capability for soil reclamation are zeolites, zero-valent iron nanoparticles (NPs), iron oxide NPs, phosphate-based NPs, iron sulfide NPs, and Carbon nanotubes. However, the use of SS on agricultural soils may be constrained by the presence of PTEs. If sewage sludge-based PTE concentrations exceed the threshold limits, they may pollute the food chain and ultimately endanger human health (Antoniadis et al., 2019). As a result, lowering PTEs availability in soils amended with SS is very important from an agricultural and environmental perspective. The inclusion of materials having high retention capacities, like geomaterials (GMs) and nanoparticles (NPs), may improve a soil's capability to hold PTEs (Dan et al., 2020; Lu and Astruc, 2018). Geomaterials (zeolite and bentonite) have strong sorption potential for PTEs due to their large surface area and negative charge (Shaheen et al., 2015; Tahervand and Jalali, 2017). As a result, these geomaterials can stabilize PTEs in SS and contaminated soils with SS (Shaheen et al., 2014), but further research is required to determine how zeolite and bentonite, particularly when combined with NPs, affect the competitive and single-metal sorption of PTEs found in SS treated soils. Various synthesized metal oxide nanoparticles are used for the sorption of PTEs and immobilize them in soils due to their strong chemical efficiency and large surface area (Ibrahim et al., 2016). In a few investigations, PTEs were immobilized in soils using metal oxide nanoparticles (Ettler et al., 2015; Liu et al., 2020). One of the studies explored how geo materials such as zeolite and bentonite and nanoparticles such as ZnO and MgO affected the competitive adsorption of various metals, including Cd^{2+} , Cu^{2+} , Ni^{2+} , and Zn^{2+} , in an alkali soil augmented with three different concentrations of sewage sludge. In the soil that had been treated with SS, the nanoparticles and geo materials dramatically enhanced Cd^{2+} , Cu^{2+} , Ni^{2+} , and Zn^{2+} sorption. As compared to the GMs, nanoparticles efficiency for the mono-sorption of copper and zinc was substantially higher. Contrarily, the GMs considerably higher the NPs in terms of Cd metal mono-sorption.

The NPs demonstrated more sorption than the GMs for all PTEs in the competitive sorption of metals. Compared to the GMs, the NPs showed a greater ability for Zn sorption with the three sewage sludge-treated soil. We conclude that zeolite, bentonite, ZnO, and MgO have complicated interactions with the adsorption of Cd^{2+} , Cu^{2+} , Ni^{2+} , and Zn^{2+} and are highly specific to PTEs and SS sources. Regarding waste management techniques and reclamation of SS-amended soils by adsorption of PTEs, reactive GMs, and introduced NPs can be helpful for a successful environmental treatment. We are concerned that field-scale verification of modified GMs and synthetic NPs is necessary to validate our laboratory findings on the solubility and availability of PTEs as impacted by sewage sludges.

Additionally, particular sorption mechanisms must be investigated using spectroscopic approaches for the fate of particular PTEs in soils treated with SS, NP, and GM may be further thoroughly evaluated (Feizi et al., 2019). MgO and ZnO nanoparticles have high surface areas and reactive sites, making them effective in metal sorption. Similarly, zeolite and bentonite have large surface areas and are effective at sorbing various metals (Nagappa and Chandrappa, 2007; Qi et al., 2020). The specific trends in metal sorption were influenced by the composition of the soil and metals. (Moharami and Jalali, 2013). In another report, it is demonstrated that zeolite and bentonite sorption capability for various metals is related to their large surface area, similar to nanosized oxides (Hamidpour et al., 2011). Metal sorption using zeolite and bentonite is thought to occur through mechanisms such as ion exchange, large surface area, inner-sphere complexation, and chemisorption, with inner-sphere complexation in zeolite responsible for the irreversibility of the sorption process for both metals (Mahdavi and Akhzari, 2016; Mahdavi et al., 2015). Additionally, NPs can immobilize toxic metals by a variety of methods, including co-precipitation, reduction, physical sorption, and chemisorption (Duan et al., 2021; Jalali and Moharrami, 2007; Pan et al., 2021a).

In environmental research, a reduction in the availability of HMs is a major factor. This study examined the impact of iron oxide and nano hydroxyapatite (NHAP) on the cadmium uptake by bean plants grown in soil amended with sewage sludge. The bean plants were collected after 90 days, and the concentrations of Fe, Zn and Cd in the plants were assessed. Additionally, the rate of soil microbial respiration was estimated. The addition of NHAP to the soil boosted its Zn and Fe concentrations by 12.8 and 14.5%, respectively, in the plants grown in the soil supplemented with 15 t/ha of sewage sludge. However, there was a 17.2% reduction in the Cadmium concentration. While, Zn and Fe contents in the bean plants were dramatically enhanced by 13.1 and 14.6%, respectively, when 15 and 30 t/ha of SS were used. The foliar application of FeO NPs at a concentration of 1 ppm dramatically reduced Cd uptake by 18.3%. The proportion of SS used (30 t/h) and NHAP (0.5% (W/W)) both considerably enhanced the soil microbial respiration as well. According to the study's findings, introducing organic amendments like NHAP, sewage sludge, and application of iron oxide NPs can have a positive impact on the environment by reducing the uptake of toxic metals by plants (Baghaie and Aghilizefreeti, 2021).

6.2.1. Biochar, nano-biochar, and their nanocomposites

Biochar has recently been proposed as a soil amendment and has generated interest because of its ability to adsorb metals in contaminated soil and serve as a green environmental sorbent. Being a green environmental sorbent, biochar has been proposed as an amendment and has gained interest due to its ability to sequester metals in polluted soil (Meng et al., 2018). Biochar is a carbonaceous substance synthesized when biomass is burned in pyrolysis (Lehmann and Joseph, 2015). Puga et al. (2016) demonstrated that biochar enhances soil pH and decreases the mobility and accessible

concentrations of metals, including Cd^{2+} , Pb^{2+} , and Zn^{2+} . As a result, plants can tolerate contaminated soil, thrive, and decrease the deposition of toxic metals in soils, rendering them suited for soil restoration (Martins et al., 2018; Soudek et al., 2017). Pyrolysis of SS is a practical method for removing organic contaminants and infectious organisms while reducing volume. The resulting biochar from industrial waste can be used to enhance soil characteristics such as nutrient flow, soil pH, water retention, and carbon storage. This biochar has promising potential for use as a soil amendment due to its beneficial physicochemical properties (Randolph et al., 2017). Furthermore, combining biochar with SS may improve the efficacy of revegetation because of their distinct qualities (Bogusz and Oleszczuk, 2018; Miller-Robbie et al., 2015) examined the co-production and co-application of SS along with biochar to saline-alkali soil and reported that biochar has numerous advantages for managing SS regarding energy integration and minimizing the emission of greenhouse gases. The following are possible mechanistic strategies that could immobilize the toxic metals from the soil via biochars: (i) formation of large precipitates, (ii) metal adsorption, (iii) ions exchange and electrostatic interactions, (iv) the development of persistent chelates and complex compounds, with organic matter. According to this research, functional groups such as $-\text{OH}$, $-\text{COOH}$, and $\text{C}=\text{N}$ can bind to the transitional metals to produce stable complexes, enhancing their capacity to bind to biochar (Lu et al., 2017).

Alkali, acid, metal ions, and oxidizing agents are used to produce designed and modified biochar composites in order to modify biochar in order to enhance its physio-chemical characteristics (Lee et al., 2017; Pan et al., 2021b). Biochar has been modified using a variety of inorganic substances, including zeolites, silica, metals, and nano-metal oxides. The preparation of MgO /biochar composites, for instance, included coupled electrochemical modification. In order to adsorb contaminants and degrade them by photocatalysis, Titanium dioxide TiO_2 -coated biochar composites were created (Mandal et al., 2021). Magnetic biochar, which is biochar that has been coated with metal oxides, has a high capacity to bind pollutants like phosphate (Chen et al., 2011). The use of engineered biochar has effectively reduced the bioavailability and transport of HMs in soil settings. As an example, biochar that has been changed with sulfate or sulfate-iron may reduce the availability of Cd^{2+} , while biochar that has been altered with red mud can reduce the availability of arsenic (Li et al., 2022; Rajendran et al., 2019; Zou et al., 2018).

Modified biochar-based nanocomposites were engineered for enhanced physicochemical attributes through various modifications such as metal ions, alkali, and reducing and oxidizing agents. Some inorganic agents such as silica, chitosan, zeolites, and nano-metals and their oxides have been used for biochar modifications. For instance, MgO /biochar nanocomposites were synthesized through electrochemical modification. Titanium dioxide (TiO_2) coated biochar composites were formulated for photocatalytic degradation and adsorption of pollutants (Mandal et al., 2021). Magnetic biochar, or biochar coated with metal oxides, has demonstrated excellent adsorption capacity for pollutants such as phosphate (Chen et al., 2011). Modified biochar has been used to efficiently remove toxic metals from polluted areas, including arsenate As(V) (Rahman et al., 2021), lead, and cadmium (Wu et al., 2021). Engineered biochar has been effectively used to reduce the availability and transmission of heavy metal ions in soil environments. For instance, Rajendran et al. (2019) found that sulfur and sulfur-iron-modified biochar reduced cadmium availability, and (Zou et al., 2018) found that red mud-modified biochar reduced the availability of arsenic. However, relatively few researchers have documented the application of nano-biochar (NBC) composites to reduce toxic metals-induced toxicity and soil contamination. In one of the experiments, four crops were tested cucumber, lettuce, carrot, and tomato. The Cd pollution significantly decreased seed germination, seedling length, and their biomass. The nano-BC augmented soil reduced the plants uptake cadmium concentration. High throughput sequencing also showed that nano-BC increased the biomass, variety, and abundance of microorganisms in Cd-treated soils, particularly Bacteroidetes and Actinobacteria (Rajput et al., 2022a). There is no data reported on biochar based nanocomposites for enhancement of SS use efficiency. So as the future recommendation, the use of nanobiochar along with SS will be useful to enhance the agricultural yield as well immobilize the HMs Fig. 6.

7. Conclusion and future perspective

Saline-alkali soil has become a major environmental threat, especially in arid and semi-arid regions for crop production and agricultural sustainability. This review explicitly signifies that the application of sewage sludge is effective at managing saline-alkali soil. However, the sources, collection, utilization of SS in agriculture have challenges concerning its usefulness and environmental and health effects. While it appears beneficial regarding a strategy to reuse and manage municipal/industrial water, conserve fertilizer, and achieve specific environmental and social goals. Moreover, the nutritional importance of SS has also contributed to its extensive usage in crop production, despite several environmental and human health issues. One of the major concerns associated with this practice is the accumulation of HMs in soil, plants, food chains, and, eventually humans. When the ecological/environmental and human health problems related to crop production are evaluated globally, considering the rapid increasing of population, economic development, and unpredicted climate change, the utilization of SS in the agricultural sectors may face many challenges.

Despite the efficacy of sewage sludge to manage saline-alkali land, strategies and techniques for its application should be prioritized in saline-alkali soils to improve these soils' conditions. However, more scientific investigations are required to ensure the effective and sustainable development and implementation of sludge farming systems, especially in developing countries. Our findings highlight the issues required to be addressed in future research, such as possible mechanistic strategies that could immobilize the toxic metals from the soil and accumulation of HMs in soil-groundwater, soil-plant, and plant-human body due to utilization of sewage sludge. We have also recommended the biochar based nanocomposites for enhancement of SS use efficiency for the future studies, the use of nanobiochar along with SS can be useful to enhance the crop yield as well immobilize the HMs in soil/ groundwater and plant from the application of SS for the growth of crop.

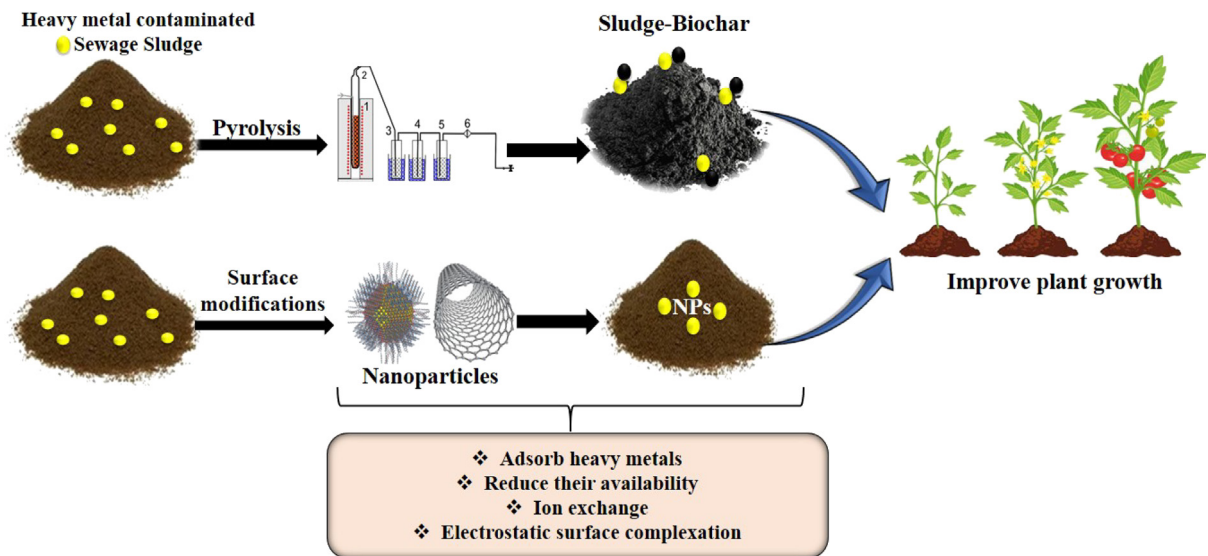


Fig. 6. Immobilization of bioavailability of heavy metals from sewage sludge by nano-biotechnology.

CRediT authorship contribution statement

Muhammad Yousuf Jat Baloch: Writing – original draft. **Wenjing Zhang:** Supervision, Funding. **Tahira Sultana:** Formal analysis, Conceptualization. **Muhammad Akram:** Formal analysis, Conceptualization. **Baig Abdullah Al Shoumik:** Review and editing. **Md. Zulfikar Khan:** Review and editing. **Muhammad Ansar Farooq:** Visualization.

Declaration of competing interest

We declare that we do not have any commercial or associative interest that represents a conflict of interest in connection with the work submitted.

Data availability

The data that has been used is confidential.

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References

- Abedin, M.A., Habiba, U., Shaw, R., 2014. Salinity scenario in mekong, ganges, and indus river deltas. In: *Water Insecurity: A Social Dilemma*. Emerald Group Publishing Limited, pp. 115–138.
- Abrol, I., Yadav, J.S.P., Massoud, F., 1988. Salt-Affected Soils and their Management. Food & Agriculture Org.
- Adam, C., Krüger, O., 2014. Complete survey of German sewage sludge ashes-phosphorous and technology metal recovery potential. In: *SUM2014-2nd Symposium on Urban Mining (Proceedings)*. Session B 4, 1–7.
- Adams, W., Hughes, F., 1990. Irrigation development in desert environments. In: *Techniques for Desert Reclamation*. pp. 135–160.

- Ahanger, M.A., Agarwal, R., 2017. Salinity stress induced alterations in antioxidant metabolism and nitrogen assimilation in wheat (*Triticum aestivum* L.) as influenced by potassium supplementation. *Plant Physiol. Biochem.* 115, 449–460.
- Ahmadpoor, S., Bahmanyar, M., Gilani, S., Forghani, A., 2011. Chemical characteristic, enzyme activity of urease and alkaline phosphatase in a soil amended with sewage sludge and sewage sludge enrichment with chemical fertilizer. *J. Soil Water Conserv.*
- Ahmed, H.K., Fawy, H.A., Abdel-Hady, E., 2010. Study of sewage sludge use in agriculture and its effect on plant and soil. *Agric. Biol. JN Am.* 1 (5), 1044–1049.
- Ahmed, I., Ofori-Amanfo, D., Awuah, E., Cobbold, F., 2019. A comprehensive study on the physicochemical characteristics of faecal sludge in greater Accra region and analysis of its potential use as feedstock for green energy. *J. Renew. Energy* 2019.
- Akram, M., Gao, B., Pan, J., Khan, R., Inam, M.A., Xu, X., Guo, K., Yue, Q., 2021. Enhanced removal of phosphate using pomegranate peel-modified nickel-lanthanum hydroxide. *Sci. Total Environ.* 151181.
- Akram, M., Xu, X., Gao, B., Wang, S., Khan, R., Yue, Q., Duan, P., Dan, H., Pan, J., 2020a. Highly efficient removal of phosphate from aqueous media by pomegranate peel co-doping with ferric chloride and lanthanum hydroxide nanoparticles. *J. Clean. Prod.* 125311.
- Akram, M., Xu, X., Gao, B., Yue, Q., Yanan, S., Khan, R., Inam, M.A., 2020b. Adsorptive removal of phosphate by the bimetallic hydroxide nanocomposites embedded in pomegranate peel. *J. Environ. Sci.* 91, 189–198.
- Albuquerque, H.C.d., Zuba Junio, G.R., Sampaio, R.A., Fernandes, L.A., Zonta, E., Barbosa, C.F., 2015. Yield and nutrition of sunflower fertilized with sewage sludge. *Rev. Bras. Eng. Agríc. Ambient.* 19, 553–559.
- Allison, L., Richards, L.A., 1954. Diagnosis and Improvement of Saline and Alkali Soils. Soil and Water Conservative Research Branch, Agricultural Research Service
- Alonge, T.A., Ojo, O.I., Adejumbi, M.A., 2018. Electrical conductivity based classification and mapping of salt affected soils in kampe-omi irrigation scheme. *GSJ* 6 (7), 1075.
- Alvarenga, P., Mourinha, C., Farto, M., Santos, T., Palma, P., Sengo, J., Morais, M.-C., Cunha-Queda, C., 2015. Sewage sludge, compost and other representative organic wastes as agricultural soil amendments: Benefits versus limiting factors. *Waste Manage.* 40, 44–52.
- Amrhein, C., 1996. Australian Sodic Soils: Distribution, Properties, and Management. LWW.
- Anderson, E., Addy, M., Ma, H., Chen, P., Ruan, R., 2016. Economic screening of renewable energy technologies: Incineration, anaerobic digestion, and biodiesel as applied to waste water scum. *Bioresour. Technol.* 222, 202–209.
- Andriamananjara, A., Rabeharisoa, L., Prud'homme, L., Morel, C., 2016. Drivers of plant-availability of phosphorus from thermally conditioned sewage sludge as assessed by isotopic labeling. *Front. Nutr.* 3, 19.
- Angin, I., Yaganoglu, A., 2012. Effects of sewage sludge application on yield, yield parameters and heavy metal content of barley grown under arid climatic conditions. *Int. J. Agric. Biol.* 14, 811–815.
- Angin, I., Yaghanoglu, A., 2011. Effects of sewage sludge application on some physical and chemical properties of a soil affected by wind erosion. *J. Agric. Sci. Technol.* 13 (5), 757–768.
- Antoniadis, V., Shaheen, S.M., Levizou, E., Shahid, M., Niazi, N.K., Vithanage, M., Ok, Y.S., Bolan, N., Rinklebe, J., 2019. A critical prospective analysis of the potential toxicity of trace element regulation limits in soils worldwide: Are they protective concerning health risk assessment?—A review. *Environ. Int.* 127, 819–847.
- Asghar, M.A., Zahir, E., Shahid, S.M., Khan, M.N., Asghar, M.A., Iqbal, J., Walker, G., 2018. Iron, copper and silver nanoparticles: Green synthesis using green and black tea leaves extracts and evaluation of antibacterial, antifungal and aflatoxin B1 adsorption activity. *Lwt* 90, 98–107.
- Assis, A.S., Otenio, M.H., Drumond, B.P., Fumian, T.M., Miagostovich, M.P., da Rosa, M.L., 2017. Optimization of the skimmed-milk flocculation method for recovery of adenovirus from sludge. *Sci. Total Environ.* 583, 163–168.
- Association, I.W., 2013. In: Lazarova, V. (Ed.), *Milestones in Water Reuse: The Best Success Stories*. IWA Pub, London.
- Atienza-Martínez, M., Rubio, I., Fonts, I., Ceamanos, J., Gea, G., 2017. Effect of torrefaction on the catalytic post-treatment of sewage sludge pyrolysis vapors using γ -Al₂O₃. *Chem. Eng. J.* 308, 264–274.
- Badaou, A.N.A.D., Altun, M., Demir, A.D., Sahin, U., Kiziloglu, F.M., 2022. Wetting-drying cycles with wastewater after freezing-thawing of clay soil containing sewage sludge improve hydraulic properties. *Environ. Eng. Manag. J. (EEMJ)* 21 (9).
- Badaou, A.A.D., Sahin, U., 2022. Effects of sewage sludge amendment and wetting–drying cycles of wastewater irrigation on structural improvement of clay soil. *Int. J. Environ. Sci. Technol.* 19 (7), 6453–6466.
- Baghaie, A.H., Aghilizefere, A., 2021. Nano Fe-oxide and nano-hydroxyapatite can decrease the Cd uptake by plant in a soil treated with Cd-polluted sewage sludge. *J. Water Environ. Nanotechnol.* 6 (2), 188–195.
- Bai, Y., Zang, C., Gu, M., Gu, C., Shao, H., Guan, Y., Wang, X., Zhou, X., Shan, Y., Feng, K., 2017. Sewage sludge as an initial fertility driver for rapid improvement of mudflat salt-soils. *Sci. Total Environ.* 578, 47–55.
- Balboa, S., Mauricio-Iglesias, M., Rodriguez, S., Martínez-Lamas, L., Vasallo, F.J., Regueiro, B., Lema, J.M., 2021. The fate of SARS-COV-2 in WWTPS points out the sludge line as a suitable spot for detection of COVID-19. *Sci. Total Environ.* 772, 145268.
- Balcom, I.N., Driscoll, H., Vincent, J., Leduc, M., 2016. Metagenomic analysis of an ecological wastewater treatment plant's microbial communities and their potential to metabolize pharmaceuticals. *FRsearch* 5.
- Balkhair, K.S., Ashraf, M.A., 2016. Field accumulation risks of heavy metals in soil and vegetable crop irrigated with sewage water in western region of Saudi Arabia. *Saudi J. Biol. Sci.* 23 (1), S32–S44.
- Barber, L.B., Thurman, E.M., Schroeder, M.P., LeBlanc, D.R., 1988. Long-term fate of organic micropollutants in sewage-contaminated groundwater. *Environ. Sci. Technol.* 22 (2), 205–211.
- Barnabé, S., Beauchesne, I., Cooper, D., Nicell, J., 2008. Plasticizers and their degradation products in the process streams of a large urban physicochemical sewage treatment plant. *Water Res.* 42 (1–2), 153–162.
- Bennett, S.J., Barrett-Lennard, E., Colmer, T., 2009. Salinity and waterlogging as constraints to saltland pasture production: a review. *Agric. Ecosyst. Environ.* 129 (4), 349–360.
- Bernal, M., Albuquerque, J., Moral, R., 2009. Composting of animal manures and chemical criteria for compost maturity assessment. A review. *Bioresour. Technol.* 100 (22), 5444–5453.
- Bettiol, W., Ghini, R., 2011. Impacts of sewage sludge in tropical soil: a case study in Brazil. *Appl. Environ. Soil Sci.*
- Bhattacharyya, R., Ghosh, B.N., Mishra, P.K., Mandal, B., Rao, C.S., Sarkar, D., Das, K., Anil, K.S., Lalitha, M., Hati, K.M., 2015. Soil degradation in India: Challenges and potential solutions. *Sustainability* 7 (4), 3528–3570.
- Bianchini, A., Bonfiglioli, L., Pellegrini, M., Saccani, C., 2016. Sewage sludge management in Europe: a critical analysis of data quality. *Int. J. Environ. Waste Manag.* 18 (3), 226–238.
- Bibby, K., Peccia, J., 2013. Identification of viral pathogen diversity in sewage sludge by metagenome analysis. *Environ. Sci. Technol.* 47 (4), 1945–1951.
- Bielińska, E.J., Kołodziej, B., Wiśniewski, J., Kawecka-Radomska, M., 2015. The effect of different doses of sewage sludge on soil chemical properties located within municipal landfill. *P.P.H. Zapol Dmochowski Sobczyk Sp. J. Szc.* 17–25.
- Bofill-Mas, S., Albinana-Gimenez, N., Clemente-Casares, P., Hunders, A., Rodriguez-Manzano, J., Allard, A., Calvo, M., Girones, R., 2006. Quantification and stability of human adenoviruses and polyomavirus JCPyV in wastewater matrices. *Appl. Environ. Microbiol.* 72 (12), 7894–7896.
- Bogusz, A., Oleszczuk, P., 2018. Sequential extraction of nickel and zinc in sewage sludge-or biochar/sewage sludge-amended soil. *Sci. Total Environ.* 636, 927–935.

- Bot, A., Benites, J., 2005. The Importance of Soil Organic Matter: Key to Drought-Resistant Soil and Sustained Food Production. Food & Agriculture Org.
- Boudjabi, S., Chenchouni, H., 2021. On the sustainability of land applications of sewage sludge: how to apply the sewage biosolid in order to improve soil fertility and increase crop yield? *Chemosphere* 282, 131122.
- Burges, A., Alkorta, I., Epelde, L., Garbisu, C., 2018. From phytoremediation of soil contaminants to phytomanagement of ecosystem services in metal contaminated sites. *Int. J. Phytoremediation* 20 (4), 384–397.
- Buta, M., Hubeny, J., Zieliński, W., Harnisz, M., Korzeniewska, E., 2021. Sewage sludge in agriculture the effects of selected chemical pollutants and emerging genetic resistance determinants on the quality of soil and crops – a review. *Ecotoxicol. Environ. Saf.* 214, 112070.
- Casado-Vela, J., Sellés, S., Díaz-Crespo, C., Navarro-Pedreño, J., Mataix-Beneyto, J., Gómez, I., 2007. Effect of composted sewage sludge application to soil on sweet pepper crop (*Capsicum annuum* var. *annuum*) grown under two exploitation regimes. *Waste Manage.* 27 (11), 1509–1518.
- Černý, J., Balík, J., Kulhánek, M., Vašák, F., Peklová, L., Sedlár, O.J.P., 2012. The effect of mineral N fertiliser and sewage sludge on yield and nitrogen efficiency of silage maize. *Plant Soil Environ.* 58 (2), 76–83.
- Chang, A.C., Pan, G., Page, A.L., Asano, T., 2001. Developing Human Health-Related Chemical Guidelines for Reclaimed Waster and Sewage Sludge Applications in Agriculture. World Health Organization European Environmental Bureau, 13.
- Chen, B., Chen, Z., Lv, S., 2011. A novel magnetic biochar efficiently sorbs organic pollutants and phosphate. *Bioresour. Technol.* 102 (2), 716–723.
- Chen, H., Yan, S., Ye, Z., Meng, H., Zhu, Y., 2012. Utilization of urban sewage sludge: Chinese perspectives. *Environ. Sci. Pollut. Res.* 19, 1454–1463.
- Christiansen, M., 1982. World environmental limitations to food and fiber culture.
- Christou, A., Eliadou, E., Michael, C., Hapeshi, E., Fatta-Kassinos, D., 2014. Assessment of long-term wastewater irrigation impacts on the soil geochemical properties and the bioaccumulation of heavy metals to the agricultural products. *Environ. Monit. Assess.* 186, 4857–4870.
- Ciešlik, B.M., Namieśnik, J., Konieczka, P., 2015. Review of sewage sludge management: standards, regulations and analytical methods. *J. Clean. Prod.* 90, 1–15.
- Corcoran, E., 2010. Sick Water?: The Central Role of Wastewater Management in Sustainable Development: A Rapid Response Assessment. UNEP/Earthprint.
- Council, N.R., 1996. Use of Reclaimed Water and Sludge in Food Crop Production. National Academies Press.
- Cuevas, G., Martínez, F., Walter, I., 2003. Field-grown maize (*Zea mays* L.) with composted sewage sludge. Effects on soil and grain quality. *Span. J. Agric. Res.* 1 (3), 111–119.
- Curci, M., Lavecchia, A., Cucci, G., Lacolla, G., De Corato, U., Crecchio, C., 2020. Short-term effects of sewage sludge compost amendment on semiarid soil. *Soil Syst.* 4 (3), 48.
- Cydzik-Kwiatkowska, A., Zielińska, M., 2016. Bacterial communities in full-scale wastewater treatment systems. *World J. Microbiol. Biotechnol.* 32, 1–8.
- da Silva Oliveira, A., Bocio, A., Beltrami Trevilato, T.M., Magosso Takayanagui, A.M., Domingo, J.L., Segura-Muñoz, S.I., 2007. Heavy metals in untreated/treated urban effluent and sludge from a biological wastewater treatment plant. *Environ. Sci. Pollut. Res.-Int.* 14, 483–489.
- Dagar, J.C., Yadav, R.K., Sharma, P.C., 2019. Research Developments in Saline Agriculture. Springer.
- Dan, H., Li, N., Xu, X., Gao, Y., Huang, Y., Akram, M., Yin, W., Gao, B., Yue, Q., 2020. Mechanism of sonication time on structure and adsorption properties of 3D peanut shell/graphene oxide aerogel. *Sci. Total Environ.* 739, 139983.
- Delibacak, S., Voronina, L., Morachevskaya, E., 2020. Use of sewage sludge in agricultural soils: Useful or harmful. *Eurasian J. Soil Sci.* 9 (2), 126–139.
- Dilpazeer, F., Munir, M., Baloch, M.Y.J., Shafiq, I., Iqbal, J., Saeed, M., Abbas, M.M., Shafique, S., Aziz, K.H.H., Mustafa, A., Mahboob, I., 2023. A comprehensive review of the latest advancements in controlling arsenic contaminants in groundwater. *Water* 15 (3), 478.
- Division, A.D.o.E.E.S., 2001. Guidelines for the Application of Municipal Wastewater Sludges to Agricultural Lands. Government of Alberta.
- Dove, A., 2017. Central California is losing \$3.7 billion in crop yield every year. In: Report from Department of Civil and Environmental Engineering. Carnegie Mellon University, Pittsburgh, PA, USA, <https://engineering.cmu.edu>.
- Duan, P., Liu, X., Liu, B., Akram, M., Li, Y., Pan, J., Yue, Q., Gao, B., Xu, X., 2021. Effect of phosphate on peroxymonosulfate activation: Accelerating generation of sulfate radical and underlying mechanism. *Appl. Catal. B* 298, 120532.
- Dubova, L., Cielava, N., Vibornij, V., Rimkus, A., Alsina, I., Mutere, O., Strunnikova, N., Kassien, O., 2020. Evaluation of suitability of treated sewage sludge for maize cultivation. *Key Eng. Mater.* 159–165, Trans Tech Publ.
- Egamberdieva, D., Wirth, S., Bellingrath-Kimura, S.D., Mishra, J., Arora, N.K., 2019. Salt-tolerant plant growth promoting rhizobacteria for enhancing crop productivity of saline soils. *Front. Microbiol.* 10, 2791.
- Eid, E.M., Alamri, S.A., Shaltout, K.H., Galal, T.M., Ahmed, M.T., Brima, E.I., Sewelam, N., 2020. A sustainable food security approach: Controlled land application of sewage sludge recirculates nutrients to agricultural soils and enhances crop productivity. *Food Energy Secur.* 9 (2), e197.
- El-Nahhal, I.Y., Al-Najar, H., El-Nahhal, Y., 2014. Physicochemical properties of sewage sludge from Gaza. *Int. J. Geosci.* 2014.
- Ettler, V., Tomášová, Z., Komárek, M., Mihaljevič, M., Šebek, O., Michálková, Z., 2015. The pH-dependent long-term stability of an amorphous manganese oxide in smelter-polluted soils: implication for chemical stabilization of metals and metalloids. *J. Hard Mater.* 286, 386–394.
- Evelin, H., Devi, T.S., Gupta, R., Kapoor, R., 2019. Mitigation of salinity stress in plants by arbuscular mycorrhizal symbiosis: current understanding and new challenges. *Front. Plant Sci.* 10, 470.
- FAO, L., 2008. Plant Nutrition Management Service. Land and Water Development Division, Food and Agriculture Organization of the United Nations Rome.
- FAO, I.a.I.I., 2012. Jrc: Harmonized World Soil Database (Version 1.2). FAO, Rome, Italy IIASA, Laxenburg, Austria.
- FAO, I., 2015a. Status of the World's Soil Resources (SWSR)—Main Report. Rome. Italy.
- FAO, I., 2015b. Status of the World's Soil Resources (SWSR)—Main Report. Food Agriculture Organization of the United Nations Intergovernmental Technical Panel on Soils.
- Feigin, A., Ravina, I., Shalhevet, J., 2012. Irrigation with Treated Sewage Effluent: Management for Environmental Protection. Springer Science & Business Media.
- Feizi, M., Jalali, M., Antoniadis, V., Shaheen, S.M., Ok, Y.S., Rinklebe, J., 2019. Geo-and nano-materials affect the mono-metal and competitive sorption of Cd, Cu, Ni, and Zn in a sewage sludge-treated alkaline soil. *J. Hard Mater.* 379, 120567.
- Fernández-Luqueño, F., Marsch, R., Espinosa-Victoria, D., Thalasso, F., Lara, M.H., Munive, A., Luna-Guido, M., Dendooven, L., 2008. Remediation of PAHs in a saline-alkaline soil amended with wastewater sludge and the effect on dynamics of C and N. *Sci. Total Environ.* 402 (1), 18–28.
- Fijalkowski, K., Rorat, A., Grobelak, A., Kacprzak, M.J., 2017. The presence of contaminations in sewage sludge—The current situation. *J. Environ. Manag.* 203, 1126–1136.
- Fischer, G., Shah, M., Van Velthuisen, H., Nachtergaele, F.O., 2001. Global Agro-Ecological Assessment for Agriculture in the 21st Century. Fließbach, A., Martens, R., Reber, H., 1994. Soil microbial biomass and microbial activity in soils treated with heavy metal contaminated sewage sludge. *Soil Biol. Biochem.* 26 (9), 1201–1205.
- Fonts, I., Azuara, M., Gea, G., Murillo, M., 2009. Study of the pyrolysis liquids obtained from different sewage sludge. *J. Anal. Appl. Pyrolysis* 85 (1–2), 184–191.
- Fytli, D., Zabanitout, A., 2008. Utilization of sewage sludge in EU application of old and new methods—A review. *Renew. Sustain. Energy Rev.* 12 (1), 116–140.

- Gao, P., He, S., Huang, S., Li, K., Liu, Z., Xue, G., Sun, W., 2015. Impacts of coexisting antibiotics, antibacterial residues, and heavy metals on the occurrence of erythromycin resistance genes in urban wastewater. *Appl. Microbiol. Biotechnol.* 99, 3971–3980.
- Gao, N., Quan, C., Liu, B., Li, Z., Wu, C., Li, A., 2017. Continuous pyrolysis of sewage sludge in a screw-feeding reactor: products characterization and ecological risk assessment of heavy metals. *Energy Fuels* 31 (5), 5063–5072.
- García-Gil, J., Plaza, C., Senesi, N., Brunetti, G., Polo, A., 2004. Effects of sewage sludge amendment on humic acids and microbiological properties of a semiarid Mediterranean soil. *Biol. Fertil. Soils* 39, 320–328.
- Geilfus, C.-M., 2018. Chloride: from nutrient to toxicant. *Plant Cell Physiol.* 59 (5), 877–886.
- Geng, H., Xu, Y., Zheng, L., Gong, H., Dai, L., Dai, X., 2020. An overview of removing heavy metals from sewage sludge: Achievements and perspectives. *Environ. Pollut.* 266, 115375.
- Gengmao, Z., Yu, H., Xing, S., Shihui, L., Quanmei, S., Changhai, W., 2015. Salinity stress increases secondary metabolites and enzyme activity in safflower. *Ind. Crops Prod.* 64, 175–181.
- Ghassemi, F., Jakeman, A.J., Nix, H.A., 1995. *Salinisation of Land and Water Resources: Human Causes, Extent, Management and Case Studies*. CAB international.
- Gholipour, S., Rabbani, D., Nikaeen, M., 2021. Presence of coronavirus, enterovirus and adenovirus in municipal wastewater as indicators of the prevalence of associated viral infections in the community. *J. Mazandaran Univ. Med. Sci.* 31 (197), 44–54.
- Goldan, E., Nedeff, V., Barsan, N., Culea, M., Tomozei, C., Panainte-Lehadus, M., Mosnegutu, E., 2022. Evaluation of the use of sewage sludge biochar as a soil amendment—A review. *Sustainability* 14 (9), 5309.
- González, D., Colón, J., Gabriel, D., Sánchez, A., 2019. The effect of the composting time on the gaseous emissions and the compost stability in a full-scale sewage sludge composting plant. *Sci. Total Environ.* 654, 311–323.
- Goossens, R., Van Ranst, E., 1998. The use of remote sensing to map gypsiferous soils in the Ismailia Province (Egypt). *Geoderma* 87 (1–2), 47–56.
- Gopalakrishnan, T., Kumar, L., 2020. Modeling and mapping of soil salinity and its impact on Paddy Lands in Jaffna Peninsula, Sri Lanka. *Sustainability* 12 (20), 8317.
- Gorgec, A.G., Insel, G., Yağci, N., Doçru, M., Erdiñçler, A., Sanin, D., Filibeli, A., Keskinler, B., Çoğkır, E., 2016. Comparison of energy efficiencies for advanced anaerobic digestion, incineration, and gasification processes in municipal sludge management. *J. Residuals Sci. Technol.* 13 (1).
- Grüter, H., Matter, M., Oehlmann, K., Hicks, M., 1990. Drying of sewage sludge—An important step in waste disposal. *Water Sci. Technol.* 22 (12), 57–63.
- Gu, C., Bai, Y., Tao, T., Chen, G., Shan, Y., 2013. Effect of sewage sludge amendment on heavy metal uptake and yield of ryegrass seedling in a mudflat soil. *J. Environ. Qual.* 42 (2), 421–428.
- Guangyin, Z., Youcai, Z., 2017. Chapter one. Sewage sludge generation and characteristics. In: *Pollution Control Resource Recovery*. pp. 1–11.
- Guest, J.S., Skerlos, S.J., Barnard, J.L., Beck, M.B., Daigger, G.T., Hilger, H., Jackson, S.J., Karvazy, K., Kelly, L., Macpherson, L., 2009. *A New Planning and Design Paradigm to Achieve Sustainable Resource Recovery from Wastewater*. ACS Publications.
- Gul, S., Naz, A., Fareed, I., Irshad, M., 2015. Reducing heavy metals extraction from contaminated soils using organic and inorganic amendments—a review. *Pol. J. Environ. Stud.* 24 (3), 1423–1426.
- Guo, H., van Lier, J.B., de Kreuk, M., 2020. Digestibility of waste aerobic granular sludge from a full-scale municipal wastewater treatment system. *Water Res.* 173, 115617.
- Haghighat, M., Majidian, N., Hallajisani, A., 2020. Production of bio-oil from sewage sludge: A review on the thermal and catalytic conversion by pyrolysis. *Sustain. Energy Technol. Assess.* 42, 100870.
- Hamidpour, M., Kalbasi, M., Afyuni, M., Shariatmadari, H., Furrer, G., 2011. Sorption of lead on Iranian bentonite and zeolite: kinetics and isotherms. *Environ. Earth Sci.* 62, 559–568.
- Hassanli, A.M., Javan, M., Saadat, Y., 2008. Reuse of municipal effluent with drip irrigation and evaluation the effect on soil properties in a semi-arid area. *Environ. Monit. Assess.* 144, 151–158.
- He, J., Zhang, Y., Cheng, G., 2015. Research progress in technologies of heavy metals from urban sewage sludge. *Appl. Chem. Ind.* 44, 1541–1546.
- Hernández, T., Moreno, J.L., Costa, F., 1991. Influence of sewage sludge application on crop yields and heavy metal availability. *Soil Sci. Plant Nutr.* 37 (2), 201–210.
- Hewitt, J., Greening, G.E., Leonard, M., Lewis, G.D., 2013. Evaluation of human adenovirus and human polyomavirus as indicators of human sewage contamination in the aquatic environment. *Water Res.* 47 (17), 6750–6761.
- Hong, J., Xu, C., Hong, J., Tan, X., Chen, W., 2013. Life cycle assessment of sewage sludge co-incineration in a coal-based power station. *Waste Manage.* 33 (9), 1843–1852.
- Hornick, H., Sikora, L., Sterrett, S., 1984. *Utilization of Sewage Sludge Compost as a Soil Conditioner and Fertilizer for Plant Growth*. RP.
- Hossain, M.S., 2019. Present scenario of global salt affected soils, its management and importance of salinity research. *Int. Res. J. Biol. Sci.* 1 (1), 1–3.
- Hu, S.-H., Hu, S.-C., Fu, Y.-P., 2012a. Resource recycling through artificial lightweight aggregates from sewage sludge and derived ash using boric acid flux to lower co-melting temperature. *J. Air Waste Manag. Assoc.* 62 (2), 262–269.
- Hu, Y., Schmidhalter, U., 2023. Opportunity and challenges of phenotyping plant salt tolerance. *Trends Plant Sci.*
- Hu, M., Wang, X., Wen, X., Xia, Y., 2012b. Microbial community structures in different wastewater treatment plants as revealed by 454-pyrosequencing analysis. *Bioresour. Technol.* 117, 72–79.
- Hu, J., Wu, F., Wu, S., Cao, Z., Lin, X., Wong, M.H., 2013. Bioaccessibility, dietary exposure and human risk assessment of heavy metals from market vegetables in Hong Kong revealed with an in vitro gastrointestinal model. *Chemosphere* 91 (4), 455–461.
- Huang, Z., Lu, Q., Wang, J., Chen, X., Mao, X., He, Z., 2017. Inhibition of the bioavailability of heavy metals in sewage sludge biochar by adding two stabilizers. *PLoS One* 12 (8), e0183617.
- Hurley, R.R., Lusher, A.L., Olsen, M., Nizzetto, L., 2018. Validation of a method for extracting microplastics from complex, organic-rich, environmental matrices. *Environ. Sci. Technol.* 52 (13), 7409–7417.
- Ibarbalz, F.M., Figuerola, E.L., Erijman, L., 2013. Industrial activated sludge exhibit unique bacterial community composition at high taxonomic ranks. *Water Res.* 47 (11), 3854–3864.
- Ibrahim, R.K., Hayyan, M., AlSaadi, M.A., Hayyan, A., Ibrahim, S., 2016. Environmental application of nanotechnology: air, soil, and water. *Environ. Sci. Pollut. Res.* 23, 13754–13788.
- Iglesias, M., Marguí, E., Camps, F., Hidalgo, M., 2018. Extractability and crop transfer of potentially toxic elements from mediterranean agricultural soils following long-term sewage sludge applications as a fertilizer replacement to barley and maize crops. *Waste Manage.* 75, 312–318.
- Ilyas, F., 2017. Sindh suffers 31pc crop loss annually due to waterlogging, salinity. *Dawn*.
- Iqbal, J., Su, C., Rashid, A., Yang, N., Baloch, M.Y.J., Talpur, S.A., Ullah, Z., Rahman, G., Rahman, N.U., Sajjad, M.M., 2021. Hydrogeochemical assessment of groundwater and suitability analysis for domestic and agricultural utility in Southern Punjab, Pakistan. *Water* 13 (24), 3589.
- Iqbal, J., Su, C., Wang, M., Abbas, H., Baloch, M.Y.J., Ghani, J., Ullah, Z., Huq, M.E., 2023. Groundwater fluoride and nitrate contamination and associated human health risk assessment in South Punjab, Pakistan. *Environ. Sci. Pollut. Res.* 30 (22), 61606–61625.
- Iticescu, C., Georgescu, P.-L., Arseni, M., Rosu, A., Timofti, M., Carp, G., Cioca, L.-I., 2021. Optimal solutions for the use of sewage sludge on agricultural lands. *Water* 13 (5), 585.

- Izah, S.C., Ngum, C.T., Iniaighe, P.O., Aigberua, A.O., Odubo, T.C., 2023. Chapter 13 - Processes of decontamination and elimination of toxic metals from water and wastewaters. In: Shukla, S.K., Kumar, S., Madhav, S., Mishra, P.K. (Eds.), *Metals in Water*. Elsevier, pp. 239–262.
- Jahn, R., Blume, H., Asio, V., Spaargaren, O., Schad, P., 2006. Guidelines for Soil Description. FAO.
- Jalali, M., Moharrami, S., 2007. Competitive adsorption of trace elements in calcareous soils of western Iran. *Geoderma* 140 (1–2), 156–163.
- Jamil, M., Qasim, M., Umar, M., Rehman, K., 2004. Impact of organic wastes (sewage sludge) on the yield of wheat (*Triticum aestivum* L.) in a calcareous soil. *Int. J. Agric. Biol.* 6 (3), 465–467.
- Jamil, A., Riaz, S., Ashraf, M., Foolad, M., 2011. Gene expression profiling of plants under salt stress. *Crit. Rev. Plant Sci.* 30 (5), 435–458.
- Jat Baloch, M.Y., Mangi, S.H., 2019. Treatment of synthetic greywater by using banana, orange and sapodilla peels as a low cost activated carbon. *J. Mater. Environ. Sci.* 10 (10), 966–986.
- Jat Baloch, M.Y., Su, C., Talpur, S.A., Iqbal, J., Bajwa, K., 2023. Arsenic removal from groundwater using iron pyrite: Influence factors and removal mechanism. *J. Earth Sci.* 1–11.
- Jat Baloch, M.Y., Talpur, S.A., Talpur, H.A., Iqbal, J., Mangi, S.H., Memon, S., 2020. Effects of arsenic toxicity on the environment and its remediation techniques: A review. *J. Water Environ. Technol.* 18 (5), 275–289.
- Jat Baloch, M.Y., Zhang, W., Chai, J., Li, S., Alqurashi, M., Rehman, G., Tariq, A., Talpur, S.A., Iqbal, J., Munir, M., 2021. Shallow groundwater quality assessment and its suitability analysis for drinking and irrigation purposes. *Water* 13 (23), 3361.
- Jat Baloch, M.Y., Zhang, W., Shoumik, B.A.A., Nigar, A., Elhassan, A.A., Elshekh, A.E., Bashir, M.O., Mohamed Salih Ebrahim, A.F., Adam Mohamed, K.A., Iqbal, J., 2022a. Hydrogeochemical mechanism associated with land use land cover indices using geospatial, remote sensing techniques, and health risks model. *Sustainability* 14 (24), 16768.
- Jat Baloch, M.Y., Zhang, W., Zhang, D., Al Shoumik, B.A., Iqbal, J., Li, S., Chai, J., Farooq, M.A., Parkash, A., 2022b. Evolution mechanism of arsenic enrichment in groundwater and associated health risks in Southern Punjab, Pakistan. *Int. J. Environ. Res. Public Health* 19 (20), 13325.
- Javed, B., Ikram, M., Farooq, F., Sultana, T., Mashwani, Z.-u.-R., Raja, N.I., 2021. Biogenesis of silver nanoparticles to treat cancer, diabetes, and microbial infections: A mechanistic overview. *Appl. Microbiol. Biotechnol.* 105, 2261–2275.
- Jebri, S., Jofre, J., Barkallah, I., Saidi, M., Hmaied, F., 2012. Presence and fate of coliphages and enteric viruses in three wastewater treatment plants effluents and activated sludge from Tunisia. *Environ. Sci. Pollut. Res.* 19, 2195–2201.
- Jia, Y., Wu, J., Cheng, M., Xia, X., 2023. Global transfer of salinization on irrigated land: Complex network and endogenous structure. *J. Environ. Manag.* 336, 117592.
- Jiang, Y., Zhou, P., Zhang, P., Adeel, M., Shakoar, N., Li, Y., Li, M., Guo, M., Zhao, W., Lou, B., 2022. Green synthesis of metal-based nanoparticles for sustainable agriculture. *Environ. Pollut.* 119755.
- Jiao, Y., 2021. Chapter 2 - Waste to biohydrogen: potential and feasibility. In: Zhang, Q., He, C., Ren, J., Goodsite, M. (Eds.), *Waste to Renewable Biohydrogen*. Academic Press, pp. 33–53.
- Jolly, Y.N., Islam, A., Akbar, S., 2013. Transfer of metals from soil to vegetables and possible health risk assessment. *SpringerPlus* 2, 1–8.
- Jorge, F.C., Dinis, M.A.P., 2013. Sewage sludge disposal with energy recovery: A review. *Proc. Inst. Civ. Eng.-Waste Resour. Manag.* 1, 4–28, ICE Publishing.
- Joshi, A., Breulmann, M., Schulz, E., Ruser, R., 2022. Effects of sewage sludge hydrochar on emissions of the climate-relevant trace gases N₂O and CO₂ from loamy sand soil. *Heliyon* 8 (10), e10855.
- Kabata-Pendias, A., 2011. Trace Elements in Soils and Plants/Fourth Editions. CRC Taylor Francis Group, Boca Raton, 505.
- Kelepertzis, E., 2014. Accumulation of heavy metals in agricultural soils of mediterranean: Insights from Argolida basin, Peloponnese, Greece. *Geoderma* 221, 82–90.
- Kelessidis, A., Stasinakis, A.S., 2012. Comparative study of the methods used for treatment and final disposal of sewage sludge in European countries. *Waste Manage.* 32 (6), 1186–1195.
- Khan, A.S., 2012. Nanotechnology: Ethical and Social Implications. CRC Press.
- Khan, R., Inam, M.A., Akram, M., Uddin, A., Khan, S., Yeom, I.T., 2019. Effect of dissolved organic matter on agglomeration and removal of CuO nanoparticles by coagulation. *Processes* 7 (7), 455.
- Khan, M.Z., Shoumik, B.A.A., 2022. Land degradation neutrality concerns in Bangladesh. *Soil Security* 9, 100075, <https://doi.org/10.1016/j.soisec.2022.100075>.
- Kinkle, B.K., Angle, J.S., Keyser, H.H., 1987. Long-term effects of metal-rich sewage sludge application on soil populations of bradyrhizobium japonicum. *Appl. Environ. Microbiol.* 53 (2), 315–319.
- Kirchmann, H., Börjesson, G., Kätterer, T., Cohen, Y., 2017. From agricultural use of sewage sludge to nutrient extraction: A soil science outlook. *Ambio* 46, 143–154.
- Konuma, H., 2018. Status and outlook of global food security and the role of underutilized food resources: Sago palm. In: *Sago Palm: Multiple Contributions to Food Security Sustainable Livelihoods*. pp. 3–16.
- Korboulewsky, N., Dupouyet, S., Bonin, G., 2002. Environmental risks of applying sewage sludge compost to vineyards: carbon, heavy metals, nitrogen, and phosphorus accumulation. *J. Environ. Qual.* 31 (5), 1522–1527.
- Koutroubas, S.D., Antoniadis, V., Damalas, C.A., Fotiadis, S., 2023. Municipal sewage sludge effects on maize yield, nitrogen use efficiency, and soil properties. *J. Soil Sci. Plant Nutr.* 1–13.
- Koutroubas, S.D., Antoniadis, V., Fotiadis, S., Damalas, C.A., 2014. Growth, grain yield and nitrogen use efficiency of mediterranean wheat in soils amended with municipal sewage sludge. *Nutr. Cycl. Agroecosyst.* 100, 227–243.
- Kumar, M., Dutta, S., You, S., Luo, G., Zhang, S., Show, P.L., Sawarkar, A.D., Singh, L., Tsang, D.C., 2021. A critical review on biochar for enhancing biogas production from anaerobic digestion of food waste and sludge. *J. Clean. Prod.* 305, 127143.
- Kunhikrishnan, A., Bolan, N.S., Müller, K., Laurenson, S., Naidu, R., Kim, W.-I., 2012. The influence of wastewater irrigation on the transformation and bioavailability of heavy metal (loid)s in soil. *Adv. Agron.* 115, 215–297.
- Lakhdar, A., Scelza, R., Scotti, R., Rao, M.A., Jedidi, N., Gianfreda, L., Abdelly, C., 2010. The effect of compost and sewage sludge on soil biologic activities in salt affected soil. *Rev. Cienc. Suelo Nutr. Veg.* 10 (1), 40–47.
- Lassoued, N., Essaid, B., 2022. Impact of the spreading of sludge from wastewater treatment plants on the transfer and bio-availability of trace metal elements in the soil-plant system. In: *Wastewater Treatment*, Vol. 133.
- Latare, A., Kumar, O., Singh, S., Gupta, A., 2014. Direct and residual effect of sewage sludge on yield, heavy metals content and soil fertility under rice-wheat system. *Ecol. Eng.* 69, 17–24.
- Lee, J., Kim, K.-H., Kwon, E.E., 2017. Biochar as a catalyst. *Renew. Sustain. Energy Rev.* 77, 70–79.
- Lehmann, J., Joseph, S., 2015. *Biochar for Environmental Management: Science, Technology and Implementation*. Routledge.
- Leijenhörst, E.J., Wolters, W., Van De Beld, L., Prins, W., 2016. Inorganic element transfer from biomass to fast pyrolysis oil: Review and experiments. *Fuel Process. Technol.* 149, 96–111.
- Levidow, L., Zaccaria, D., Maia, R., Vivas, E., Todorovic, M., Scardigno, A., 2014. Improving water-efficient irrigation: Prospects and difficulties of innovative practices. *Agricult. Water Manag.* 146, 84–94.
- Lewis, D.L., Gattie, D.K., 2002. Peer reviewed: pathogen risks from applying sewage sludge to land. *Environ. Sci. Technol.* 36 (13), 286A–293A.

- Li, J., Ding, S., Wang, F., Zhao, H., Kou, J., Akram, M., Xu, M., Gao, W., Liu, C., Yang, H., Dong, Z., 2022. Platinum clusters anchored on sulfur-doped ordered mesoporous carbon for chemoselective hydrogenation of halogenated nitroarenes. *J. Colloid Interface Sci.* 625, 640–650.
- Li, Q., Tang, J., Wang, T., Wu, D., Busso, C.A., Jiao, R., Ren, X., 2017. Impacts of sewage irrigation on soil properties of farmland in China: A review. *Solid Earth Discuss.* 1–24.
- Li, S., Zhang, W., Zhang, D., Xiu, W., Wu, S., Chai, J., Ma, J., Baloch, M.Y.J., Sun, S., Yang, Y.J.E.P., 2023. Migration risk of *Escherichia coli* O157: H7 in unsaturated porous media in response to different colloid types and compositions. 121282.
- Lima, V.N., Silva, R.V.T.O., Nunes, P., da Silva, P.H., Morant, K., Andrade, R.F., Nascimento, A.E., Campos-Takaki, G.M., Messias, A.S., 2016. The cumulative effects of sewage sludge compost on *Raphanus sativus* L: Growth and soil properties. *Green Sustain. Chem.* 6 (01), 1.
- Liu, H., 2018. Novel approach on reduction in GHG emissions from sludge lime stabilization as an emergent and regional treatment in China. *Sci. Rep.* 8 (1), 16564.
- Liu, R., Lal, R., 2012. Nanoenhanced materials for reclamation of mine lands and other degraded soils: a review. *J. Nanotechnol.* 2012.
- Liu, J.-y., Sun, S.-y., 2013. Total concentrations and different fractions of heavy metals in sewage sludge from Guangzhou, China. *Trans. Nonfer. Met. Soc. China* 23 (8), 2397–2407.
- Liu, Y., Sun, T., Su, Q., Tang, Y., Xu, X., Akram, M., Jiang, B., 2020. Highly efficient and mild electrochemical degradation of bentazon by nano-diamond doped PbO₂ anode with reduced Ti nanotube as the interlayer. *J. Colloid Interface Sci.* 575, 254–264.
- Lloret, E., Pascual, J.A., Brodie, E.L., Bouskill, N.J., Insam, H., Juárez, M.F.-D., Goberna, M., 2016. Sewage sludge addition modifies soil microbial communities and plant performance depending on the sludge stabilization process. *Appl. Soil Ecol.* 101, 37–46.
- Logan, B.E., Hamelers, B., Rozendal, R., Schröder, U., Keller, J., Freguía, S., Aelterman, P., Verstraete, W., Rabaey, K., 2006. Microbial fuel cells: methodology and technology. *Environ. Sci. Technol.* 40 (17), 5181–5192.
- Lu, F., Astruc, D., 2018. Nanomaterials for removal of toxic elements from water. *Coord. Chem. Rev.* 356, 147–164.
- Lu, K., Yang, X., Gielen, G., Bolan, N., Ok, Y.S., Niazi, N.K., Xu, S., Yuan, G., Chen, X., Zhang, X., 2017. Effect of bamboo and rice straw biochars on the mobility and redistribution of heavy metals (Cd, Cu, Pb and Zn) in contaminated soil. *J. Environ. Manag.* 186, 285–292.
- Ma, Q., Qu, Y., Shen, W., Zhang, Z., Wang, J., Liu, Z., Li, D., Li, H., Zhou, J., 2015. Bacterial community compositions of coking wastewater treatment plants in steel industry revealed by Illumina high-throughput sequencing. *Bioresour. Technol.* 179, 436–443.
- Ma, Y., Tashpolat, N., 2023. Current status and development trend of soil salinity monitoring research in China. *Sustainability* 15 (7), 5874.
- Machnicka, A., Grübel, K., 2023. The effect of pre-treatment and anaerobic digestion for pathogens reduction in agricultural utilization of sewage sludge. *Environ. Sci. Pollut. Res.* 30 (5), 13801–13810.
- Madejón, E., Burgos, P., López, R., Cabrera, F., 2001. Soil enzymatic response to addition of heavy metals with organic residues. *Biol. Fertil. Soils* 34, 144–150.
- Mahar, A., Wang, P., Ali, A., Awasthi, M.K., Lahori, A.H., Wang, Q., Li, R., Zhang, Z., 2016. Challenges and opportunities in the phytoremediation of heavy metals contaminated soils: a review. *Ecotoxicol. Environ. Saf.* 126, 111–121.
- Mahdavi, S., Akhbari, D., 2016. The removal of phosphate from aqueous solutions using two nano-structures: copper oxide and carbon tubes. *Clean Technol. Environ. Policy* 18, 817–827.
- Mahdavi, S., Jalali, M., Afkhami, A.J.C.t., policy, e., 2015. Heavy metals removal from aqueous solutions by Al₂O₃ nanoparticles modified with natural and chemical modifiers. *Clean Technol. Environ. Policy* 17, 85–102.
- Manara, P., Zabaniotou, A., 2012. Towards sewage sludge based biofuels via thermochemical conversion—A review. *Renew. Sustain. Energy Rev.* 16 (5), 2566–2582.
- Mandal, S., Pu, S., Adhikari, S., Ma, H., Kim, D.-H., Bai, Y., Hou, D., 2021. Progress and future prospects in biochar composites: Application and reflection in the soil environment. *Crit. Rev. Environ. Sci. Technol.* 51 (3), 219–271.
- Mansoor, N., Kausar, S., Amjad, S.F., Yaseen, S., Shahid, H., tul Kubra, K., Alamri, S.A., Alrumman, S.A., Eid, E.M., Mustafa, G., 2021. Application of sewage sludge combined with thiourea improves the growth and yield attributes of wheat (*Triticum aestivum* L.) genotypes under arsenic-contaminated soil. *Plos One* 16 (11), e0259289.
- Marguí, E., Iglesias, M., Camps, F., Sala, L., Hidalgo, M., 2016. Long-term use of biosolids as organic fertilizers in agricultural soils: potentially toxic elements occurrence and mobility. *Environ. Sci. Pollut. Res.* 23, 4454–4464.
- Marschner, P., Kandeler, E., Marschner, B., 2003. Structure and function of the soil microbial community in a long-term fertilizer experiment. *Soil Biol. Biochem.* 35 (3), 453–461.
- Martinez-Beltran, J., 2005. Overview of salinity problems in the world and FAO strategies to address the problem, Managing saline soils and water: science, technology and social issues. In: *Proceedings of the International Salinity Forum*. Riverside, California, 2005.
- Martins, G.C., Penido, E.S., Alvarenga, I.F.S., Teodoro, J.C., Bianchi, M.L., Guilherme, L.R.G., 2018. Amending potential of organic and industrial by-products applied to heavy metal-rich mining soils. *Ecotoxicol. Environ. Saf.* 162, 581–590.
- Masciaglioli, T., Zhang, W.-X., 2003. Peer Reviewed: Environmental Technologies at the Nanoscale. ACS Publications.
- Mathakiya, H., Meisheri, M., 2007. Feasibility of using some solid industrial wastes on cabbage and their effect on yield and nutrient absorption. *J. Indian Soc. Soil Sci.* 55 (2), 227–230.
- Maw, M.M., Boontanon, N., Fujii, S., Boontanon, S.K., 2022. Rapid and efficient removal of organic matter from sewage sludge for extraction of microplastics. *Sci. Total Environ.* 853, 158642.
- Mbagwu, J., Piccolo, A., 1990. Carbon, nitrogen and phosphorus concentrations in aggregates of organic waste-amended soils. *Biol. Wastes* 31 (2), 97–111.
- Meena, A., Kumari, S., Lekshmi, N., Kumar, C., Kumar, S., 2020. Sewage sludge application in agriculture: impact on crops and human health. *Food Sci. Rep.* 1, 53–58.
- Mehmood, T., Bibi, I., Shahid, M., Niazi, N.K., Murtaza, B., Wang, H., Ok, Y.S., Sarkar, B., Javed, M.T., Murtaza, G., 2017. Effect of compost addition on arsenic uptake, morphological and physiological attributes of maize plants grown in contrasting soils. *J. Geochem. Explor.* 178, 83–91.
- Meng, F., Jiang, J., Zhao, Q., Wang, K., Wei, L., Ma, L., Zheng, Z., 2014. Effect of sludge application on physicochemical properties of saline alkali soil and wheat growing. *Environ. Sci. Technol.* 37 (9), 126–132.
- Meng, J., Tao, M., Wang, L., Liu, X., Xu, J., 2018. Changes in heavy metal bioavailability and speciation from a Pb-Zn mining soil amended with biochars from co-pyrolysis of rice straw and swine manure. *Sci. Total Environ.* 633, 300–307.
- Menz, J., Müller, J., Olsson, O., Kümmerer, K., 2018. Bioavailability of antibiotics at soil–water interfaces: a comparison of measured activities and equilibrium partitioning estimates. *Environ. Sci. Technol.* 52 (11), 6555–6564.
- Miller-Robbie, L., Ulrich, B.A., Ramey, D.F., Spencer, K.S., Herzog, S.P., Cath, T.Y., Stokes, J.R., Higgins, C.P., 2015. Life cycle energy and greenhouse gas assessment of the co-production of biosolids and biochar for land application. *J. Clean. Prod.* 91, 118–127.
- Mininni, G., Blanch, A., Lucena, F., Berselli, S., 2015. EU policy on sewage sludge utilization and perspectives on new approaches of sludge management. *Environ. Sci. Pollut. Res.* 22, 7361–7374.
- Modi, A., Khatri, N., Tyagi, S., Jha, A., 2022. Analysis of contaminants in sewage and groundwater: future impact on human and animal health. *Environ. Sci. Pollut. Res.* 34 (3), 208–221.
- Modolo, L.V., da Silva, C.J., Brandão, D.S., Chaves, I.S., 2018. A minireview on what we have learned about urease inhibitors of agricultural interest since mid-2000s. *J. Adv. Res.* 13, 29–37.

- Moharami, S., Jalali, M., 2013. Removal of phosphorus from aqueous solution by Iranian natural adsorbents. *Chem. Eng. J.* 223, 328–339.
- Moolenaar, S., Beltrami, P., 1998. Heavy Metal Balances of an Italian Soil as Affected by Sewage Sludge and Bordeaux Mixture Applications. Wiley Online Library.
- Mora, A., Torres-Martínez, J.A., Capparelli, M.V., Zabala, A., Mahlknecht, J., 2022. Effects of wastewater irrigation on groundwater quality: An overview. *Curr. Opin. Environ. Sci. Health* 25, 100322.
- Mtshali, J.S., Tiruneh, A.T., Fadiran, A.O., 2014. Characterization of sewage sludge generated from wastewater treatment plants in Swaziland in relation to agricultural uses. *Resour. Environ.* 4 (4), 190–199.
- Muamar, A., Zouahri, A., Tijane, M.h., El Housni, A., Mennane, Z., Yachou, H., Bouksaim, M., 2014. Evaluation of heavy metals pollution in groundwater, soil and some vegetables irrigated with wastewater in the Skhirat region Morocco. *J. Mater. Environ. Sci.* 5 (3), 961–966.
- Mukhopadhyay, R., Sarkar, B., Jat, H.S., Sharma, P.C., Bolan, N.S., 2021. Soil salinity under climate change: Challenges for sustainable agriculture and food security. *J. Environ. Manag.* 280, 111736.
- Murakami, T., Suzuki, Y., Nagasawa, H., Yamamoto, T., Koseki, T., Hirose, H., Okamoto, S., 2009. Combustion characteristics of sewage sludge in an incineration plant for energy recovery. *Fuel Process. Technol.* 90 (6), 778–783.
- Mustapha, M.A., Manan, Z.A., Alwi, S.R.W., 2017. A new quantitative overall environmental performance indicator for a wastewater treatment plant. *J. Clean. Prod.* 167, 815–823.
- Muter, O., Dubova, L., Kassien, O., Cakane, J., Alsina, I., 2022. Application of the sewage sludge in agriculture: Soil fertility, technoeconomic, and life-cycle assessment. *Hazard. Waste Manag.* 125.
- Nabati, J., Kafi, M., Nezami, A., Moghaddam, P.R., Ali, M., Mehrjerdi, M.Z., 2011. Effect of salinity on biomass production and activities of some key enzymatic antioxidants in kochia (*Kochia scoparia*). *Pak. J. Bot.* 43 (1), 539–548.
- Nagappa, B., Chandrappa, G., 2007. Mesoporous nanocrystalline magnesium oxide for environmental remediation. *Microporous Mesoporous Mater.* 106 (1–3), 212–218.
- Ni, H., Fan, X.-M., Guo, H.-N., Liang, J.-H., Li, Q.-R., Yang, L., Li, H., Li, H.-H., 2017. Comprehensive utilization of activated sludge for the preparation of hydrolytic enzymes, polyhydroxyalkanoates, and water-retaining organic fertilizer. *Prep. Biochem. Biotechnol.* 47 (6), 611–618.
- Nielsen, P.H., Mielczarek, A.T., Kragelund, C., Nielsen, J.L., Saunders, A.M., Kong, Y., Hansen, A.A., Vollertsen, J., 2010. A conceptual ecosystem model of microbial communities in enhanced biological phosphorus removal plants. *Water Res.* 44 (17), 5070–5088.
- Novak, J., Trapp, S., 2005. Growth of plants on TBT-contaminated harbour sludge and effect on TBT removal (10 pp). *Environ. Sci. Pollut. Res.* 12, 332–341.
- Olujimi, O.O., Fatoki, O.S., Odendaal, J., Daso, A.P., Oputu, O., 2012. Preliminary investigation into occurrence and removal of arsenic, cadmium, mercury, and zinc in wastewater treatment plants in cape town and Stellenbosch. *Pol. J. Environ. Stud.* 21 (6).
- Orhon, D., 1997. Modeling of Activated Sludge Systems. CRC Press.
- Orlov, D., Sadovnikova, L., 2005. Soil organic matter and protective functions of humic. In: Use of Humic Substances to Remediate Polluted Environments: From Theory to Practice. p. 37.
- Outhman, A., Firdous, F., 2016. The impact of the use of sludge in agriculture on the vegetative growth of cereal crops. *Int. J. Adv. Ind. Eng.* 4, 1–9.
- Özyazici, M.A., 2013. Effects of sewage sludge on the yield of plants in the rotation system of wheat-white head cabbage-tomato. *Eurasian J. Soil Sci.* 2 (1), 35–44.
- Pagani, A., Mallarino, A., 2012. Soil pH and crop grain yield as affected by the source and rate of lime. *Soil Sci. Am. J.* 76, 1877–1886.
- Palansooriya, K.N., Shaheen, S.M., Chen, S.S., Tsang, D.C., Hashimoto, Y., Hou, D., Bolan, N.S., Rinklebe, J., Ok, Y.S., 2020. Soil amendments for immobilization of potentially toxic elements in contaminated soils: A critical review. *Environ. Int.* 134, 105046.
- Pan, J., Gao, B., Duan, P., Guo, K., Akram, M., Xu, X., Yue, Q., Gao, Y., 2021a. Improving peroxymonosulfate activation by copper ion-saturated adsorbent-based single atom catalysts for the degradation of organic contaminants: electron-transfer mechanism and the key role of Cu single atoms. *J. Mater. Chem. A*.
- Pan, J., Gao, B., Gao, Y., Duan, P., Guo, K., Akram, M., Xu, X., Yue, Q., 2021b. In-situ Cu-doped carbon-supported catalysts applied for high-salinity polycarbonate plant wastewater treatment and a coupling application. *Chem. Eng. J.* 416, 129441.
- Peccia, J., Westerhoff, P., 2015. We Should Expect more Out of Our Sewage Sludge. ACS Publications.
- Picariello, E., Pucci, L., Carotenuto, M., Libralato, G., Lofrano, G., Baldantoni, D., 2020. Compost and sewage sludge for the improvement of soil chemical and biological quality of mediterranean agroecosystems. *Sustainability* 13 (1), 26.
- Pisinaras, V., Tsihrintzis, V., Petalas, C., Ouzounis, K., 2010. Soil salinization in the agricultural lands of Rhodope District, northeastern Greece. *Environ. Monit. Assess.* 166, 79–94.
- Pitman, M.G., Läuchli, A., 2002. Global impact of salinity and agricultural ecosystems. In: Salinity: Environment-Plants-Molecules. pp. 3–20.
- Prado, T., Gaspar, A.M.C., Miagostovich, M.P., 2014. Detection of enteric viruses in activated sludge by feasible concentration methods. *Braz. J. Microbiol.* 45, 343–349.
- Puga, A.P., Melo, L.C.A., de Abreu, C.A., Coscione, A.R., Paz-Ferreiro, J., 2016. Leaching and fractionation of heavy metals in mining soils amended with biochar. *Soil Tillage Res.* 164, 25–33.
- Pulido-Bosch, A., Rigol-Sanchez, J.P., Vallejos, A., Andreu, J., Ceron, J., Molina-Sanchez, L., Sola, F., 2018. Impacts of agricultural irrigation on groundwater salinity. *Environ. Earth Sci.* 77, 1–14.
- Puy, A., Borgonovo, E., Lo Piano, S., Levin, S.A., Saltelli, A., 2021. Irrigated areas drive irrigation water withdrawals. *Nature Commun.* 12 (1), 4525.
- Qadir, M., Noble, A., Schubert, S., Thomas, R.J., Arslan, A., 2006. Sodicty-induced land degradation and its sustainable management: Problems and prospects. *Land Degrad. Dev.* 17 (6), 661–676.
- Qadir, M., Quillérrou, E., Nangia, V., Murtaza, G., Singh, M., Thomas, R.J., Drechsel, P., Noble, A.D., 2014. Economics of salt-induced land degradation and restoration. *Nat. Resour. Forum* 282–295, Wiley Online Library.
- Qi, Y., Ge, B., Zhang, Y., Jiang, B., Wang, C., Akram, M., Xu, X., 2020. Three-dimensional porous graphene-like biochar derived from *Enteromorpha* as a persulfate activator for sulfamethoxazole degradation: role of graphitic N and radicals transformation. *J. Hard Mater.* 123039.
- Raheem, A., Sikarwar, V.S., He, J., Dastyar, W., Dionysiou, D.D., Wang, W., Zhao, M., 2018. Opportunities and challenges in sustainable treatment and resource reuse of sewage sludge: A review. *Chem. Eng. J.* 337, 616–641.
- Rahman, M.A., Lamb, D., Rahman, M.M., Bahar, M.M., Sanderson, P., Abbasi, S., Bari, A.F., Naidu, R., 2021. Removal of arsenate from contaminated waters by novel zirconium and zirconium-iron modified biochar. *J. Hard Mater.* 409, 124488.
- Rajendran, M., Shi, L., Wu, C., Li, W., An, W., Liu, Z., Xue, S., 2019. Effect of sulfur and sulfur-iron modified biochar on cadmium availability and transfer in the soil-rice system. *Chemosphere* 222, 314–322.
- Rajput, V.D., Minkina, T., Ahmed, B., Singh, V.K., Mandzhieva, S., Sushkova, S., Bauer, T., Verma, K.K., Shan, S., van Hullebusch, E.D., 2022a. Nano-biochar: A novel solution for sustainable agriculture and environmental remediation. *Environ. Res.* 210, 112891.
- Rajput, V.D., Yadav, A.N., Jatav, H.S., Singh, S.K., Minkina, T., 2022b. Sustainable Management and Utilization of Sewage Sludge. Springer.
- Rames, E., Roiko, A., Stratton, H., Macdonald, J., 2016. Technical aspects of using human adenovirus as a viral water quality indicator. *Water Res.* 96, 308–326.
- Randolph, P., Bansode, R., Hassan, O., Rehrah, D., Ravella, R., Reddy, M., Watts, D., Novak, J., Ahmedna, M., 2017. Effect of biochars produced from solid organic municipal waste on soil quality parameters. *J. Environ. Manag.* 192, 271–280.

- Rasouli, F., Pouya, A.K., Karimian, N., 2013. Wheat yield and physico-chemical properties of a sodic soil from semi-arid area of Iran as affected by applied gypsum. *Geoderma* 193, 246–255.
- Rasul, G., Appuhn, A., Müller, T., Joergensen, R.G., 2006. Salinity-induced changes in the microbial use of sugarcane filter cake added to soil. *Appl. Soil Ecol.* 31 (1–2), 1–10.
- Rattan, R., Datta, S., Chhonkar, P., Suribabu, K., Singh, A., 2005. Long-term impact of irrigation with sewage effluents on heavy metal content in soils, crops and groundwater—a case study. *Agric. Ecosyst. Environ.* 109 (3–4), 310–322.
- Rehman, R.A., Rizwan, M., Qayyum, M.F., Ali, S., Zia-ur-Rehman, M., Zafar-ul-Hye, M., Hafeez, F., Iqbal, M.F., 2018. Efficiency of various sewage sludges and their biochars in improving selected soil properties and growth of wheat (*Triticum aestivum*). *J. Environ. Manag.* 223, 607–613.
- Rengasamy, P., 2006. World salinization with emphasis on Australia. *J. Exp. Bot.* 57 (5), 1017–1023.
- Rengasamy, P., 2016. Soil salinization. In: *Oxford Research Encyclopedia of Environmental Science*.
- Rhodes, E.R., Boczek, L.A., Ware, M.W., McKay, M., Hoelle, J.M., Schoen, M., Villegas, E.N., 2015. Determining pathogen and indicator levels in class B municipal organic residuals used for land application. *J. Environ. Qual.* 44 (1), 265–274.
- Risk, N., Snider, D., Wagner-Riddle, C., 2013. Mechanisms leading to enhanced soil nitrous oxide fluxes induced by freeze–thaw cycles. *Can. J. Soil Sci.* 93 (4), 401–414.
- Roy, T., Singh, R., Biswas, D., Patra, A., 2013. Effect of sewage sludge and inorganic fertilizers on productivity and micronutrients accumulation by Palak (*Beta vulgaris*) and their availability in a Typic Haplustept. *J. Indian Soc. Soil Sci.* 61 (3), 207–218.
- Ruan, X.-D., Liu, J.-X., 2013. Analysis of the fractal structure of activated sludge flocs. *Huanjing Kexue* 34 (4), 1457–1463.
- Rulkens, W., 2008. Sewage sludge as a biomass resource for the production of energy: overview and assessment of the various options. *Energy Fuels* 22 (1), 9–15.
- Sahin, U., Angin, I., Kiziloglu, F.M., 2008. Effect of freezing and thawing processes on some physical properties of saline–sodic soils mixed with sewage sludge or fly ash. *Soil Tillage Res.* 99 (2), 254–260.
- Samaras, V., Kallianou, C., 2000. Effect of sewage sludge application on cotton yield and contamination of soils and plant leaves. *Commun. Soil Sci. Plant Anal.* 31 (3–4), 331–343.
- Samaras, V., Tsadilas, C.D., Stamatiadis, S., 2008. Effects of repeated application of municipal sewage sludge on soil fertility, cotton yield, and nitrate leaching. *Agron. J.* 100 (3), 477–483.
- Samolada, M., Zabanitout, A., 2014. Comparative assessment of municipal sewage sludge incineration, gasification and pyrolysis for a sustainable sludge-to-energy management in Greece. *Waste Manage.* 34 (2), 411–420.
- Sandra, P., 1989. *Water for Agriculture: Facing the Limits*.
- Sänger, M., Werther, J., Ogada, T., 2001. NO_x and N₂O emission characteristics from fluidised bed combustion of semi-dried municipal sewage sludge. *Fuel* 80 (2), 167–177.
- Satir, O., Berberoglu, S., 2016. Crop yield prediction under soil salinity using satellite derived vegetation indices. *Field Crops Res.* 192, 134–143.
- Scherer, T.F., Seelig, B., Franzen, D., 1996. Soil, water and plant characteristics important to irrigation.
- Schlindwein, A., Rigotto, C., Simões, C., Barardi, C., 2010. Detection of enteric viruses in sewage sludge and treated wastewater effluent. *Water Sci. Technol.* 61 (2), 537–544.
- Schöniger-Hekele, M., Petermann, D., Weber, B., Müller, C., 2007. *Tropheryma whippelii* in the environment: survey of sewage plant influents and sewage plant workers. *Appl. Environ. Microbiol.* 73 (6), 2033–2035.
- Sehler, R., Li, J., Reager, J.T., Ye, H., 2019. Investigating relationship between soil moisture and precipitation globally using remote sensing observations. *J. Contemp. Water Res. Educ.* 168 (1), 106–118.
- Semblante, G.U., Hai, F.I., Huang, X., Ball, A.S., Price, W.E., Nghiem, L.D., 2015. Trace organic contaminants in biosolids: impact of conventional wastewater and sludge processing technologies and emerging alternatives. *J. Hard Mater.* 300, 1–17.
- Setia, R., Gottschalk, P., Smith, P., Marschner, P., Baldock, J., Setia, D., Smith, J., 2013. Soil salinity decreases global soil organic carbon stocks. *Sci. Total Environ.* 465, 267–272.
- Shafiepour, S., Ayati, B., Ganjidoust, H., 2011. Reuse of sewage sludge for agricultural soil improvement (Case study: Kish island). *J. Water Wastewater* 22 (2), 85–93.
- Shaheen, S., Rinklebe, J., Selim, M., 2015. Impact of various amendments on immobilization and phytoavailability of nickel and zinc in a contaminated floodplain soil. *Int. J. Environ. Sci. Technol.* 12, 2765–2776.
- Shaheen, S., Shams, M., Ibrahim, S., Elbehiry, F., Antoniadis, V., Hooda, P., 2014. Stabilization of sewage sludge by using various by-products: effects on soil properties, biomass production, and bioavailability of copper and zinc. *Water Air Soil Pollut.* 225, 1–13.
- Shahid, M., Niazi, N.K., Khalid, S., Murtaza, B., Bibi, I., Rashid, M.I., 2018. A critical review of selenium biogeochemical behavior in soil-plant system with an inference to human health. *Environ. Pollut.* 234, 915–934.
- Shahid, M., Shamshad, S., Rafiq, M., Khalid, S., Bibi, I., Niazi, N.K., Dumat, C., Rashid, M.I., 2017. Chromium speciation, bioavailability, uptake, toxicity and detoxification in soil-plant system: A review. *Chemosphere* 178, 513–533.
- Shan, Y., Lv, M., Zuo, W., Tang, Z., Ding, C., Yu, Z., Shen, Z., Gu, C., Bai, Y., 2021. Sewage sludge application enhances soil properties and rice growth in a salt-affected mudflat soil. *Sci. Rep.* 11 (1), 1402.
- Sharma, H.D., Reddy, K.R., 2004. *Geoenvironmental Engineering: Site Remediation, Waste Containment, and Emerging Waste Management Technologies*. John Wiley & Sons.
- Sharma, M., Yadav, A., Mandal, M.K., Pandey, S., Pal, S., Chaudhuri, H., Chakrabarti, S., Dubey, K.K., 2022. Wastewater treatment and sludge management strategies for environmental sustainability. In: *Circular Economy and Sustainability*. Elsevier, pp. 97–112.
- Shekarzifard, M., 2012. Remediation of Tri-Butyltin (TBT) and Heavy Metal Contaminated Sludge by Freezing/Thawing Method.
- Shi, Y.-X., Wu, S.-H., Zhou, S.-H., Wang, C.-H., Chen, H., 2016. Simulation of the absorption, migration and accumulation process of heavy metal elements in soil-crop system. *Huanjing Kexue* 37 (10), 3996–4003.
- Shortle, J.S., Abler, D.G., Ribaud, M., 2001. Agriculture and water quality: the issues. In: *Environmental Policies for Agricultural Pollution Control*. CABI Publishing, Wallingford UK, pp. 1–18.
- Shrivastava, P., Kumar, R., 2015. Soil salinity: A serious environmental issue and plant growth promoting bacteria as one of the tools for its alleviation. *Saudi J. Biol. Sci.* 22 (2), 123–131.
- Sidhu, J.P., Toze, S.G., 2009. Human pathogens and their indicators in biosolids: a literature review. *Environ. Int.* 35 (1), 187–201.
- Simões-Mota, A., Virto, I., Poch, R.M., 2022. Effects of long-term sewage sludge application to a calcareous soil structure. *Soil Use Manag.* 38 (4), 1693–1704.
- Šindelá, O., Adamcová, D., Zloch, J., Daria Vavrková, M., 2020. Phytotoxicity of sewage sludge from selected wastewater treatment plants—new opportunities in sewage sludge treatment. *Int. J. Recycl. Org. Waste Agric.* 9 (1), 75–83.
- Singh, J., 2018. 3 - Role of earthworm in sustainable agriculture. In: *Sustainable Food Systems from Agriculture to Industry*. Academic Press, pp. 83–122.
- Singh, R., Agrawal, M., 2008. Potential benefits and risks of land application of sewage sludge. *Waste Manage.* 28 (2), 347–358.
- Singh, N.K., Emanuel, R.E., McGlynn, B.L., Miniati, C.F., 2021. Soil moisture responses to rainfall: Implications for runoff generation. *Water Resour. Res.* 57 (9), e2020WR028827.

- Singh, J., Kalamdhad, A.S., 2011. Effects of heavy metals on soil, plants, human health and aquatic life. *Int. J. Res. Chem. Environ.* 1 (2), 15–21.
- Singh, V., Phuleria, H.C., Chandel, M.K., 2022. Unlocking the nutrient value of sewage sludge. *Water Environ. J.* 36 (2), 321–331.
- Singh, R.P., Singh, P., Ibrahim, M.H., Hashim, R., 2011. Land application of sewage sludge: physicochemical and microbial response. *Rev. Environ. Contam. Toxicol.* 214, 41–61.
- Sivapatham, P., Lettimore, J.M., Alva, A.K., Jayaraman, K., Harper, L.M., 2014. Chemical fractionation of Cu, Zn, Cd, Cr, and Pb in sewage sludge amended soils at the end of 65-d sorghum-sudan grass growth. *J. Environ. Sci. Health A* 49 (11), 1304–1315.
- Siwal, S.S., Sheoran, K., Saini, A.K., Vo, D.-V.N., Wang, Q., Thakur, V.K., 2022. Advanced thermochemical conversion technologies used for energy generation: Advancement and prospects. *Fuel* 321, 124107.
- Song, Y., Kirkwood, N., Maksimović, Č., Zheng, X., O'Connor, D., Jin, Y., Hou, D., 2019. Nature based solutions for contaminated land remediation and brownfield redevelopment in cities: A review. *Sci. Total Environ.* 663, 568–579.
- Sönmez, F., Bozkurt, M.J.A.S.S.B.-S., Science, P., 2006. Lettuce grown on calcareous soils benefit from sewage sludge. 56 (1), 17–24.
- Soudek, P., Valseca, I.R., Petrová, Š., Song, J., Vaněk, T., 2017. Characteristics of different types of biochar and effects on the toxicity of heavy metals to germinating sorghum seeds. *J. Geochem. Explor.* 182, 157–165.
- Sousa, G., Fangueiro, D., Duarte, E., Vasconcelos, E., 2011. Reuse of treated wastewater and sewage sludge for fertilization and irrigation. *Water Sci. Technol.* 64 (4), 871–879.
- Sousa, A., Figueiredo, C., 2016. Sewage sludge biochar: effects on soil fertility and growth of radish. *Biol. Agric. Hortic.* 32 (2), 127–138.
- Stabnikova, O., Goh, W.-K., Ding, H.-B., Tay, J.-H., Wang, J.-Y., 2005. The use of sewage sludge and horticultural waste to develop artificial soil for plant cultivation in Singapore. *Bioresour. Technol.* 96 (9), 1073–1080.
- Su, D., Wong, J., Jagadeesan, H., 2004. Implications of rhizospheric heavy metals and nutrients for the growth of alfalfa in sludge amended soil. *Chemosphere* 56 (10), 957–965.
- Suanon, F., Tométin, L., Dimon, B., Agani, I., Mama, D., Azandegbe, E., 2016. Utilization of sewage sludge in agricultural soil as fertilizer in the republic of Benin (West Africa): What are the risks of heavy metals contamination and spreading. *Am. J. Environ. Sci.* 12 (1), 8–15.
- Sutherland, K.P., Porter, J.W., Turner, J.W., Thomas, B.J., Looney, E.E., Luna, T.P., Meyers, M.K., Futch, J.C., Lipp, E.K., 2010. Human sewage identified as likely source of white pox disease of the threatened Caribbean elkhorn coral, *Acropora palmata*. *Environ. Microbiol.* 12 (5), 1122–1131.
- Szabo, S., Hossain, M.S., Adger, W.N., Matthews, Z., Ahmed, S., Lázár, A.N., Ahmad, S., 2016. Soil salinity, household wealth and food insecurity in tropical deltas: evidence from south-west coast of Bangladesh. *Sustain. Sci.* 11, 411–421.
- Szabolcs, I., 1987. Global problems of salt-affected soils. *Acta Agronomica Hung.*
- Szabolcs, I., 1989. *Salt-Affected Soils*. CRC Press, Inc.
- Tahervand, S., Jalali, M., 2017. Sorption and desorption of potentially toxic metals (Cd, Cu, Ni and Zn) by soil amended with bentonite, calcite and zeolite as a function of pH. *J. Geochem. Explor.* 181, 148–159.
- Talpur, S.A., Noonari, T.M., Rashid, A., Ahmed, A., Jat Baloch, M.Y., Talpur, H.A., Soomro, M.H., 2020. Hydrogeochemical signatures and suitability assessment of groundwater with elevated fluoride in unconfined aquifers Badin district, Sindh, Pakistan. *SN Appl. Sci.* 2 (6), 1–15.
- Tamrabet, L., Bouzerzour, H., Kribaa, M., Makhlof, M., 2009. The effect of sewage sludge application on durum wheat (*Triticum durum*). *Int. J. Agric. Biol.* 11, 741–745.
- Tandi, N., Nyamangara, J., Bangira, C., 2004. Environmental and potential health effects of growing leafy vegetables on soil irrigated using sewage sludge and effluent: a case of Zn and Cu. *J. Environ. Sci. Health B* 39 (3), 461–471.
- Tariq, A., Mumtaz, F., Zeng, X., Baloch, M.Y.J., Moazzam, M.F.U., 2022. Spatio-temporal variation of seasonal heat islands mapping of Pakistan during 2000–2019, using day-time and night-time land surface temperatures MODIS and meteorological stations data. *Remote Sens. Appl.: Soc. Environ.* 27, 100779.
- Tchobanoglous, G., Burton, F., Stensel, H.D., 2003. Wastewater engineering: treatment and reuse. *Am. Water Works Assoc. J.* 95 (5), 201.
- Tejada, M., Garcia, C., Gonzalez, J., Hernandez, M., 2006. Use of organic amendment as a strategy for saline soil remediation: influence on the physical, chemical and biological properties of soil. *Soil Biol. Biochem.* 38 (6), 1413–1421.
- Tezel, U., Tandukar, M., Pavlostathis, S., 2011a. Anaerobic biotreatment of municipal sewage sludge.
- Tezel, U., Tandukar, M., Pavlostathis, S.G., 2011b. Anaerobic Biotreatment of municipal sewage sludge. pp. 447–461.
- Theron, J., Walker, J.A., Cloete, T.E.J.C.r.i.m., 2008. Nanotechnology and water treatment: applications and emerging opportunities. 34 (1), 43–69.
- Thomsen, T.P., Sárossy, Z., Ahrenfeldt, J., Henriksen, U.B., Frandsen, F.J., Müller-Stöver, D.S., 2017. Changes imposed by pyrolysis, thermal gasification and incineration on composition and phosphorus fertilizer quality of municipal sewage sludge. *J. Environ. Manag.* 198, 308–318.
- Thorpe, R., Brampton, B., Robson, S., Perrault, A., 2017. Investigating the effect of an alternative feedstock on the performance of sludge powered generators: developing a theoretical model and analysing trial data. In: *Proceedings of the IWA Specialist Conference on Sludge Management: Sludgetech 2017*. International Water Association.
- Tian, Y., Zhang, J., Zuo, W., Chen, L., Cui, Y., Tan, T., 2013. Nitrogen conversion in relation to NH₃ and HCN during microwave pyrolysis of sewage sludge. *Environ. Sci. Technol.* 47 (7), 3498–3505.
- Trinh, T.N., Jensen, P.A., Dam-Johansen, K., Knudsen, N.O., Sørensen, H.R., 2013. Influence of the pyrolysis temperature on sewage sludge product distribution, bio-oil, and char properties. *Energy Fuels* 27 (3), 1419–1427.
- Tyagi, V.K., Lo, S.-L., 2013. Sludge: a waste or renewable source for energy and resources recovery? *Renew. Sustain. Energy Rev.* 25, 708–728.
- Tyła, M., 2019. Assessment of heavy metal pollution and potential ecological risk in sewage sludge from municipal wastewater treatment plant located in the most industrialized region in Poland—case study. *Int. J. Environ. Res. Public Health* 16 (13), 2430.
- Urbaniak, M., Gagała, I., Szewczyk, M., Bednarek, A., 2016. Leaching of PCBs and nutrients from soil fertilized with municipal sewage sludge. *Bull. Environ. Contam. Toxicol.* 97, 249–254.
- Urbaniak, M., Wyrwicka, A., Toloczko, W., Serwecińska, L., Zieliński, M., 2017. The effect of sewage sludge application on soil properties and willow (*Salix* sp.) cultivation. *Sci. Total Environ.* 586, 66–75.
- Usharani, K., Roopashree, K., Naik, D., 2019. Role of soil physical, chemical and biological properties for soil health improvement and sustainable agriculture. *J. Pharmacogn. Phytochem.* 8 (5), 1256–1267.
- Vaxelaire, J., Cézac, P., 2004. Moisture distribution in activated sludges: a review. *Water Res.* 38 (9), 2215–2230.
- Viader, R.P., Jensen, P.E., Ottosen, L.M., Ahrenfeldt, J., Hauggaard-Nielsen, H., 2015. Electrodialytic extraction of phosphorus from ash of low-temperature gasification of sewage sludge. *Electrochim. Acta* 181, 100–108.
- Vieira, R.F., Pazianotto, R.A.A., 2016. Microbial activities in soil cultivated with corn and amended with sewage sludge. *SpringerPlus* 5 (1), 1–16.
- Vogel, C., Exner, R.M., Adam, C., 2013. Heavy metal removal from sewage sludge ash by thermochemical treatment with polyvinylchloride. *Environ. Sci. Technol.* 47 (1), 563–567.
- Walker, D.J., Bernal, M.P., 2008. The effects of olive mill waste compost and poultry manure on the availability and plant uptake of nutrients in a highly saline soil. *Bioresour. Technol.* 99 (2), 396–403.
- Wan, C.-Y., De Wever, H., Diels, L., Thoeye, C., Liang, J.-B., Huang, L.-N., 2011. Biodiversity and population dynamics of microorganisms in a full-scale membrane bioreactor for municipal wastewater treatment. *Water Res.* 45 (3), 1129–1138.
- Wang, X., Hu, M., Xia, Y., Wen, X., Ding, K., 2012. Pyrosequencing analysis of bacterial diversity in 14 wastewater treatment systems in China. *Appl. Environ. Microbiol.* 78 (19), 7042–7047.

- Wang, X., Li, C., Zhang, B., Lin, J., Chi, Q., Wang, Y., 2016. Migration and risk assessment of heavy metals in sewage sludge during hydrothermal treatment combined with pyrolysis. *Bioresour. Technol.* 221, 560–567.
- Wang, L., Shi, Y., Chai, J., Huang, L., Wang, Y., Wang, S., Pi, K., Gerson, A.R., Liu, D., 2022. Transfer of microplastics in sludge upon Fe (II)-persulfate conditioning and mechanical dewatering. *Sci. Total Environ.* 838, 156316.
- Wang, J., Wang, J., 2007. Application of radiation technology to sewage sludge processing: a review. *J. Hard Mater.* 143 (1–2), 2–7.
- Wei, H., Tang, Y., Li, A., Yang, H., 2019. Insights into the effects of acidification on sewage sludge dewaterability through pH repeated adjustment. *Chemosphere* 227, 269–276.
- Wen-Feng, T., Fan, L., Yong-Hua, L., Hong-Qing, H., Huang, Q.-Y., 2006. Elemental composition and geochemical characteristics of iron-manganese nodules in main soils of China. *Pedosphere* 16 (1), 72–81.
- Werle, S., Wilk, R.K., 2010. A review of methods for the thermal utilization of sewage sludge: The Polish perspective. *Renew. Energy* 35 (9), 1914–1919.
- Wicke, B., Smeets, E., Dornburg, V., Vashev, B., Gaiser, T., Turkenburg, W., Faaij, A., 2011. The global technical and economic potential of bioenergy from salt-affected soils. *Energy Environ. Sci.* 4 (8), 2669–2681.
- Widyarani, Wulan, D.R., Hamidah, U., Komaruzaman, A., Rosmalina, R.T., Sintawardani, N., 2022. Domestic wastewater in Indonesia: generation, characteristics and treatment. *Environ. Sci. Pollut. Res.* 29 (22), 32397–32414.
- Wong, K., Onan, B.M., Xagorarakis, I., 2010. Quantification of enteric viruses, pathogen indicators, and *Salmonella* bacteria in class B anaerobically digested biosolids by culture and molecular methods. *Appl. Environ. Microbiol.* 76 (19), 6441–6448.
- Wong, K., Xagorarakis, I.J.E.M., assessment, 2012. A perspective on the prevalence of DNA enteric virus genomes in anaerobic-digested biological wastes. 184, 5009–5016.
- Woodard, Curran, I., 2006. 2 - Fundamentals. In: Woodard, Curran, I. (Eds.), *Industrial Waste Treatment Handbook* (Second Edition). Butterworth-Heinemann, Burlington, pp. 29–49.
- Wu, J., Wang, T., Wang, J., Zhang, Y., Pan, W.-P., 2021. A novel modified method for the efficient removal of Pb and Cd from wastewater by biochar: Enhanced the ion exchange and precipitation capacity. *Sci. Total Environ.* 754, 142150.
- Xu, H., He, P., Gu, W., Wang, G., Shao, L., 2012a. Recovery of phosphorus as struvite from sewage sludge ash. *J. Environ. Sci.* 24 (8), 1533–1538.
- Xu, H., Zhang, H., Shao, L., He, P., 2012b. Fraction distributions of phosphorus in sewage sludge and sludge ash. *Waste Biomass Valoriz.* 3, 355–361.
- Yadav, R., Minhas, P., Lal, K., Chaturvedi, R., Yadav, G., Verma, T., 2015. Accumulation of metals in soils, groundwater and edible parts of crops grown under long-term irrigation with sewage mixed industrial effluents. *Bull. Environ. Contam. Toxicol.* 95, 200–206.
- Yagmur, M., Arpalı, D., Gulser, F., 2017. The Effects of Sewage Sludge Treatment on Triticale Straw Yield and its Chemical Contents in Rainfed Condition. *Pakistan Agricultural Scientists Forum*.
- Yang, W., Cai, C., Guo, Y., Wu, H., Guo, Y., Dai, X., 2022. Diversity and fate of human pathogenic bacteria, fungi, protozoa, and viruses in full-scale sludge treatment plants. *J. Clean. Prod.* 380, 134990.
- Yang, S., Feng, W., Wang, S., Chen, L., Zheng, X., Li, X., Zhou, D., 2021. Farmland heavy metals can migrate to deep soil at a regional scale: A case study on a wastewater-irrigated area in China. *Environ. Pollut.* 281, 116977.
- Yang, G., Zhang, G., Wang, H., 2015. Current state of sludge production, management, treatment and disposal in China. *Water Res.* 78, 60–73.
- Yuan, S.-J., Dai, X.-H., 2017. Sewage sludge-based functional nanomaterials: development and applications. *Environ. Sci.: Nano* 4 (1), 17–26.
- Yuan, Y., Peng, Y., Liu, Y., Jin, B., Wang, B., Wang, S., 2014. Change of pH during excess sludge fermentation under alkaline, acidic and neutral conditions. *Bioresour. Technol.* 174, 1–5.
- Yuan-xiu, G., Gao-huan, L., Jin-feng, W., 2001. Saline-alkali land in the Yellow River Delta: amelioration zonation based on GIS. *J. Geogr. Sci.* 11 (3), 313–320.
- Yue, Y., Cui, L., Lin, Q., Li, G., Zhao, X., 2017. Efficiency of sewage sludge biochar in improving urban soil properties and promoting grass growth. *Chemosphere* 173, 551–556.
- Zaman, M., Shahid, S.A., Heng, L., Shahid, S.A., Zaman, M., Heng, L., 2018. Soil salinity: Historical perspectives and a world overview of the problem. In: *Guideline for Salinity Assessment, Mitigation Adaptation using Nuclear Related Techniques*. pp. 43–53.
- Zhang, J., 2008. The Principle and Technique of Ecological Restoration of Saline-Alkali Land. China Forestry Publishing House, Beijing.
- Zhang, J., 2020a. Forestry ecological engineering in coastal saline-alkali soils. In: *Study of Ecological Engineering of Human Settlements*. Springer, pp. 93–129.
- Zhang, J., 2020b. Soil environmental deterioration and ecological rehabilitation. In: *Study of Ecological Engineering of Human Settlements*. Springer, pp. 41–82.
- Zhang, W., Chai, J., Li, S., Wang, X., Wu, S., Liang, Z., Baloch, M.Y.J., Silva, L.F., Zhang, D., 2022a. Physiological characteristics, geochemical properties and hydrological variables influencing pathogen migration in subsurface system: What we know or not? *Geosci. Front.* 101346.
- Zhang, H., Qi, H.-Y., Zhang, Y.-L., Ran, D.-D., Wu, L.-Q., Wang, H.-F., Zeng, R.J., 2022. Effects of sewage sludge pretreatment methods on its use in agricultural applications. *J. Hard Mater.* 428, 128213.
- Zhang, W., Zhu, Y., Gu, R., Liang, Z., Xu, W., Jat Baloch, M.Y.J.I.J.o.E.R., Health, P., 2022b. Health Risk Assessment during In Situ Remediation of Cr (VI)-Contaminated Groundwater by Permeable Reactive Barriers: A Field-Scale Study. 19 (20), 13079.
- Zhihong, C., 1998. Agricultural use of sludge in China. pp. 211–217.
- Zhou, X., Jiang, G., Zhang, T., Wang, Q., Xie, G.-j., Yuan, Z., 2015. Role of extracellular polymeric substances in improvement of sludge dewaterability through peroxidation. *Bioresour. Technol.* 192, 817–820.
- Zoghalmi, R.I., Hamdi, H., Mokni-Tlili, S., Hechmi, S., Khelil, M.N., Ben Aissa, N., Moussa, M., Bousnina, H., Benzarti, S., Jedidi, N., 2020. Monitoring the variation of soil quality with sewage sludge application rates in absence of rhizosphere effect. *Int. Soil Water Conserv. Res.* 8 (3), 245–252.
- Zörb, C., Geilfus, C.M., Dietz, K.J., 2019. Salinity and crop yield. *Plant Biol.* 21, 31–38.
- Zou, Q., An, W., Wu, C., Li, W., Fu, A., Xiao, R., Chen, H., Xue, S., 2018. Red mud-modified biochar reduces soil arsenic availability and changes bacterial composition. *Environ. Chem. Lett.* 16, 615–622.
- Zunqin, W., Shouquan, Z., Renpei, Y., 1993. Chinese Saline Soil. Science Press, Beijing, China.
- Zuo, W., Gu, C., Zhang, W., Xu, K., Wang, Y., Bai, Y., Shan, Y., Dai, Q., 2019. Sewage sludge amendment improved soil properties and sweet sorghum yield and quality in a newly reclaimed mudflat land. *Sci. Total Environ.* 654, 541–549.
- Zuo, W., Shen, Z., Tang, Z., Lv, M., Ding, C., Gu, C., Bai, Y., Shan, Y., Dai, Q.J.C.i.S.S., Analysis, P., 2022. Barley Growth and Metals Accumulation in Salt-affected Mudflat Amended by Sewage Sludge. 53 (12), 1482–1497.