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IMPACTS OF CANAL WATER ON SOIL QUALITY, TOMATOES AND PUBLIC HEALTH IN DISTRICT SWABI

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Abstract
The current study evaluated the impacts of using contaminated canal water for irrigation on health and the environment in District Swabi, Khyber Pakhtunkhwa. The study determined the quality of canal water, its impacts on soil characteristics, accumulation of heavy metals in tomatoes, and health risks to humans based on heavy metal concentrations. Water, soil, and tomato samples were collected from a geographical site where the main use of water is for agriculture and heavy metal concentrations were determined for Cadmium, Lead, Chromium, and Nickel, using standard laboratory methods. In soil samples, Cd ranged from 2.9 to 4.3 mg/kg, Cr 85 to 135 mg/kg, Pb 87 to 142 mg/kg, and Ni from 40 to 68 mg/kg and most were above World health organization Standards. For canal water, a high level of metals was observed above the required limits suggested by the World Health Organization as; Cadmium was up to 0.174 mg/L (Worl Health Organization limit: 0.1 mg/L), Chromium was up to 1.378 mg/L (1.0 mg/L), Lead was up to 5.13 mg/L (0.01 mg/L), and Nickel was up to 3.887 mg/L (1.0 mg/L). Contaminated irrigation water affected metal uptake in tomato fruits directly with Cd (0.01-0.6 mg/kg), Cr (0.01-0.4 mg/kg), Pb (0.2-0.9 mg/kg) and Ni (most were safe levels, only a few cases were semi- safe). Some tomato samples were above the WHO food safety limits, with the samples of Cd, Cr, and Pb being the main exceedances. This study demonstrates that farmers are contaminating soil and food crops by using polluted canal water for irrigation. The current study suggests that contamination by heavy metals has negative impacts on the environment and humans. These studies show immediate and continuous action must be taken to monitor and evaluate regulations indicated for soil health, food safety and human health in the area.

1. Introduction

1.1 Overpopulation in Pakistan

Pakistan is facing one of the highest rates of population growth in the region, with over 240 million inhabitants at present (Qasim et al.,2023). The increase in population has put tremendous strain on the country's natural resources, land, and infrastructure. Cities are increasingly congested, as peripheral settlements move into agriculture and ecologically sensitive lands (Dodman et al.,2023). Not only does this growing population require more food, water, and housing, but it also calls for more employment and public facilities (Reader, 2022). Increase in Global population has speeded up unplanned urbanization, resulting in excessive pollution, over-drafting of groundwater, and dumping of municipal and industrial wastes in the wrong manner. Accordingly, population growth

has become a major cause of environmental deterioration in Pakistan as a major driver of increased industrial and farming output to meet the increasing socioeconomic demands (Rehman et al.,2022). To fulfill the economic needs of its burgeoning population, Pakistan has been focusing on industrial development, which has resulted in the establishment of various industrial belts, especially around the major cities and rivers (Sherazi et al., 2024). Textiles, leather tanneries, pharmaceuticals, chemicals, and food processing are some of the industries that have flourished in the last few decades. Industries discharge untreated or just treated effluents into canals, rivers, and nearby farmlands (Adnan et al.,2022). These effluents usually contain xenobiotic substances such as heavy metals (such as lead, cadmium and chromium), POPs, micropollutants and biological pollutants (Razzak et al.,2022). Poor enforcement of environmental regulations also (Khanam et al., 2023).

With a rapidly growing population, Pakistan is experiencing a rising food demand to ensure national food security (Shahzad & Amjad, 2022). Agriculture is still the mainstay of the economy, sustaining the majority of the population and contributing significantly to GDP. Nevertheless, the traditional agricultural system is under pressure to enhance the production of crops and fulfill the food requirements. This increased food demand has led to the application of fertilizers, pesticides. (Hemathilake et al.,2022). Agricultural development in the majority of the country, particularly in the peri-urban and rural areas, is unregulated and causes land degradation (Gras, 2024). As the land to be cultivated continues to shrink with more urbanization and erosion of land, farmers are forced to make the most of available space in whatever way possible. This pressure to get more out of less space has, inadvertently, culminated in the employment of polluted water for irrigation purposes, thereby endangering the quality of food as well as ecological health (Mishra, 2025).

The population growth of Pakistan is alarming. The prolonged shortage of food grains has led to a decline in the yield per hectare and poor reproduction of livestock (Sharma et al.,2023). Prevention against such risks involves ensuring that adequate national reserves are maintained, which can be drawn upon at an early stage of the crisis (Tambo et al.,2021).

1.2 Tomatoes in Daily Diet

Tomato is one of the most common foods in Pakistan daily diet, raw as well as cooked, due to its nutritional value and cooking requirement (Waheed et al., 2020). However, the impacts of climate change, i.e. rain, drought, and an increase in temperature, have significantly affected tomato cultivation. Climatic stresses reduce not only the yield of crops but also affect fruit quality and shelf life. Resultantly, to meet the increasing demand for food and have an uninterrupted supply of tomatoes, there is a growing need for frequent and consistent irrigation (Manzoor et al., 2024). Unluckily, Pakistan is confronted with extensive water scarcity, especially during the peak cultivation time. Due to the scarcity and unavailability of fresh water, the farmers are relying on the polluted water to irrigate the agricultural land. (Sajid et al., 2022). The polluted canal water becomes ecotoxic that which not only affects the soil quality and food safety but also has adverse impacts on public health. (Manisalidis et al., 2020). Such waters are usually contaminated with toxic chemicals like heavy metals like lead, cadmium, and chromium, pathogenic microorganisms, and organic contaminants. Repeated use of water for irrigation leads to bioaccumulation of toxic elements in the soil, which are taken up by plants and eventually find their way into the human food chain (Jagaba et al., 2024). Leafy vegetables and root crops are most vulnerable to contamination. Abundant research has confirmed that consumption of fruits and vegetables produced using water with such conditions has certain severe health implications, including neurological disorders, kidney problems, developmental issues, and cancer (et al., 2022)

Water is the most valuable natural resource, and because of its availability on the surface of the planet, Earth is known as the “blue planet". (Knorr et al.,2023). Because of its distinctive properties and composition, water is a matrix for

life. It is estimated that 97% of the water on the planet is saline. Only 3 % of the water is fresh. Among which, approximately 68% of water is present in the form of ice in glaciers, while 30% is present underground; however, the remaining 2% is available in the rivers and lakes on the surface of the Earth (Solanki et al.,2023). Freshwater is vital to life since it is required for home use, industrial use, and agriculture (Mishra, , 2023). According to Siddiqui(2023), water for human consumption needs to be "safe and wholesome," i.e., it must be tasteless, colorless and odorless, and free of harmful substances and germs. But as one drop in quality makes the water less beneficial to humans and other organisms, the quality of water utilized is paramount (Akhtar et al., 2021).

1.3 Water Pollution

Water pollution is described as any alteration in the physical, chemical, or biological properties of water that has a harmful effect on the health of human beings or other living organisms (Lin et al., 2022). Water is needed by human beings for drinking, bathing, domestic use, and irrigation. According to Teixeira et al. (2021), water is important for the biogeochemical reaction that takes place below the surface. Sewage, rainwater, and industrial effluents are the main sources of polluted water (Ahmed et al., 2021). The application ofcontaminated water for irrigation in the agricultural sector is hazardous. At least twenty million hectares of the planet's surface water sources, in over fifty countries, are partially or totally contaminated. (Kumar et al., 2021). In the urban and semi-urban regions of the world's poorest countries, where more than 80% of the water is polluted that is used for irrigation. (Ghosh et al., 2021). Polluted water is a complex commodity with several disadvantages (Hasan et al., 2020: Yahaya et al.,2023). The major reason for using the contaminated water for irrigation is that there is a lack of resources to treat the contaminated water before irrigation, which leads to harming the ecosystems and spreading water-borne diseases (Fida et al., 2023). Polluted water contains organic matter, plant nutrients and a vast quantity of soluble salts and heavy metals (HMs). Farmers are using contaminated water to save money (Dotaniya et al., 2023). Networks for drainage and irrigation are interconnected in Pakistan. In order to alleviate the problem of waterlogging, the drains were initially constructed to collect surplus water and floodwater. (Sultan et al.,2023). However, due to industrialization and population expansion, the drains transport the industrial and urban wastewater, which ultimately gets passed into rivers and canals (Tariq et al.,2023). Untreated urban and industrial waste is hazardous to human health and the environment (Garg et al., 2022). The drainage water carries heavy metals, organic pollutants, and pharmaceutical drugs along with some biological impurities (Singh et al., 2022). When this contaminated water is used for irrigation, it contaminates the groundwater and adds poison to our food chain (Yu et al., 2022).

1.4 Canal water

Polluted canal water for cultivation has caused soil degradation and desertification in Pakistan. The harmful chemicals present in the contaminated water are accumulated in the soil (Mahmood et al., 2021). This may alter the soil fertility and affect the indigenous microbial population. Moreover, some pollutants like heavy metals i.e, lead, cadmium, chromium, and nickel are adsorbed on the soil particles, which will affect their mobility and leaching in the soil which ultimately affect crop yields, as well as increase the possibility of such toxic elements being taken up by crops (bioaccumulation) and disturb the food chain (Pande et al., 2022). In addition to that, the presence of such pollutants not only affect the soil health, but also inhibit the biogeochemical cycle of nutrients, reducing water holding capacity, and the ability of the soil to support plant life (Goud et al.,2022). Thus, application of untreated wastewater over a long term on irrigation directly involves agricultural sustainability and environmental safety, and it is crucial that wastewater needs to be monitored regularly (Singh, 2021).

Domestic waste contains greywater from bathrooms and kitchens, blackwater from toilets, and solid waste such as food waste, plastic packaging, used papers, sanitary products, and

cleaning residues. Therefore, domestic sewage is a rich mixture of organic matter, suspended solids, fats, oils, detergents, soaps, and other cleaners, as well as phosphates, nitrates, and surfactants. Domestic waste is discharged into open drains, adjacent rivers, and irrigation canals without treatment (Parveen & Khan, 2023). These chemicals alter the pH and chemical composition of canal water, making it unsafe to be used for irrigation (Aljamali et al., 2023).

Besides HMs, some biological agents are also present in the domestic wastewater including;, including *Escherichia coli, Salmonella, Giardia, and intestinal helminths* (Wu et al., 2024). When the domestic waste-contaminated water is used for irrigation, the pathogens may be transferred to the crops, posing major public health risks in the form of diarrhea, intestinal infections, and even waterborne disease (Rahman et al.,2021).

Apart from that, plastic microparticles and persistent organic pollutants (POPs) from household products also find their way into the canal system (Akhtar et al.,2021). Over time, regular dumping of household waste into irrigation water sources causes soil bioaccumulation of poisonous substances, rendering it less fertile and disrupting microbial diversity required for healthy plant growth. Since domestic wastewater has been a major driver leading to the degradation of irrigation water for decades, there is still no suitable waste disposal and recycling system available to treat the domestic waste-contaminated water (Singh, A. (2021).

1.5 Sources, Environmental and Health Impacts of Heavy Metals

One of the problems of irrigation by polluted canal water in Pakistan is the presence of persistent and toxic heavy metals (Yu et al., 2022). These generally originate from industrial effluent (metal plating plants, battery manufacturing units, paint and dye mills, tanneries, and textile mills), urban runoff, and sewage disposal that are released in raw form into canal systems. Some of these heavy metals in canal water are lead, cadmium, chromium, nickel, copper, zinc, iron, and arsenic (Khan et al.,2021) and (Suja et al.,2024).

When agricultural land is irrigated with this Domestic waste contaminated water, heavy metals may adhere to the soil particles of the root zone and bioaccumulate by the plants (Haddad et al.,2023). For instance, lead and cadmium are significantly toxic even at trace levels and cause growth inhibition and impact crop yields (Aslam et al., 2021). Chromium and nickel suppress photosynthesis and nutrient uptake, whereas copper and zinc are needed in traces but are toxic at high levels and induce signs of toxicity in plants (Kaur et al.,2025). With the passage of time, the heavy metals not only reduce the fertility of soil but also find their way to the food chain to eventually lead to severe health issues in consumers in the form of kidney damage, cancer, neurotoxicity, and developmental issues in children (Angon et al.,2024). (Hussain et al., 2020) (Khalef et al., 2022) , (Azhar et al., 2022) and (Abotalib et al.,2023). In addition to that, the environmental concentration of HMs is enhanced through the excessive or uncontrolled usage of different pesticides and fertilizers.

Soil microorganisms play a key role in ensuring soil fertility since they recycle nutrients and decompose organic material (Nadarajan et al., 2021). Nonetheless, the presence of lead and cadmium in the soil contaminated with DWCW may inhibit the growth of soil microbiota and nutrient cycling(Naz et al., 2022). Ingestion of the crops produced with the use of HMs-contaminated tomatoes by cultivation is one common way through which humans get exposed through the food chain (Vanisree et al., 2022). Growing such plants on polluted land are not safe since their vegetative cells accumulate heavy metals (Hlihor et al., 2022) and (Jannetto et al.,2023). Continued exposure to toxic heavy metals beyond the permissible limit is in is unacceptable (Mitra et al., 2022). Cadmium is one of the most prevalent heavy metal toxicities, has a density 8.65 times that of water (Parida & 2023).

Cadmium is a poisonous heavy metal. The presence of cadmium in the irrigation canal occurs through various sources, e.g., industrial effluents, phosphate fertilizers, sewage sludge, and municipal runoff (Khatun et al.,2022). Cadmium can readily accumulate in agricultural soils,

especially when DWCW is used for irrigation for long periods of time. Cadmium can be readily absorbed and transported by plants to food tissues, therefore having a high potential for affecting food safety and human health (Suhani et al., 2021). Chronic cadmium contact in man leads to renal damage, that of the proximal tubules, and presents as proteinuria and reduced glomerular filtration rate. It influences calcium metabolism, leading to bone demineralization, bone fractures, and Itai-Itai disease a disabling bone disease found in cadmium-exposed regions owing to hyper-consumption of rice (Yan et al.,2021). Cadmium has been categorized as a Group 1 human cancer-causing causing by IARC, indicating that it is recognized to be carcinogenic to humans. Chronic exposure induces cancer of the prostate, lung, and breast. In addition, cadmium suppresses the action of antioxidant enzymes, leading to an increase in oxidative stress and cellular damage (Hu et al., 2021). In plants, the toxicity of cadmium acts to inhibit seed germination, photosynthesis through disruption of chloroplast organization, inhibition of enzyme activity, and inhibition of nutrient uptake in terms of iron, zinc, and phosphorus. It also leads to external symptoms such as chlorosis, growth retardation, and necrosis (Rasafi et al.,2022). All these interferences lead to reduced yield and quality of crops, which in vegetable and cereal crops watered with polluted sources of water is highly ominous (Vasilachi et al.,2023). Literature shows that human exposure to cadmium may target the bones, brain, lungs, kidneys and liver. However, a study conducted by Bansal (2023) concluded that human exposure to cadmium can cause nausea, vomiting, abdominal cramps, dyspnea, and muscle weakness. Moreover, prolonged exposure to Cadmium can cause pulmonary edema and death. In addition to that, Aleksandrov et al., (2021) reported that Emphysema, bronchiolitis, and alveolitis are the diseases the lungs and kidneys that have been contracted as outcomes of long-term exposure to cadmium and other chemicals of the same category through inhalation (Aleksandrov et al., 2021). Japan's Itai-itai disease revealed Cd exposure to the world at large.

Mercury is known to be toxic and to play an unknown role in humans (Yang et al., 2020). Some forms of mercury can cause congenital malformations, gastrointestinal disorders (including corrosive esophagitis and hematochezia), and spontaneous abortion (Shelar et al., 2021). Mercury poisoning is associated with heart disease, cancer, cerebrovascular infarction, emphysema, osteoporosis, proteinuria, and cataract formation in the eye (Nguyen, 2020). Examples of organic poisoning include monomethyl and dimethyl methacrylate poisoning, which can result in symptoms like erythema, gingivitis, neurological illnesses, damage to the brain and central nervous system, and congenital malformation (Taux et al., 2022).

Previous studies show that Arsenic inhibits the production of adenosine triphosphate (ATP) during respiration in addition to its effects on coenzyme formation and protein coagulation (Monteiro et al., 2021). It is potentially cancer-causing, and chronic exposure can be lethal. Another illness linked to arsenic toxicity is an anti-immune illness that develops when the body's immune system mistakenly targets a portion of the PNS, leading to nerve inflammation and subsequent paralysis of the muscles (Prakash & Verma, 2021).

Chromium occurs in the environment in two stable forms: trivalent chromium (Cr^{3+}), a naturally occurring trace element which occurs in very small quantities, and hexavalent chromium (Cr^{6+}), a highly toxic as well as carcinogenic form (Vincent, 2023). Hexavalent chromium (Cr^{6+}) pervades irrigation canals and hence reaches agricultural lands. Cr^{6+} is very mobile in water and soil and easily penetrates biological membranes. Once it enters the human body, it becomes vulnerable to intracellular reduction, and thus it results in the formation of reactive intermediates, oxidative stress, DNA strand breakage, and gene mutation (Islam et al.,2023). Toxic effects of Cr^{6+} include extreme conditions such as dermatitis, liver and kidney damage, respiratory problems like ulceration of the nasal septum and lung cancer-causing factors. In addition to that Cr^{6+} is teratogenic and mutagenic, which may cause birth abnormalities and gene alterations (Hossini et

al.,2022). Other than that, Chromium induces morphological and physiological activity in plants. It prevents photosynthetic pigment formation, germination of seeds, root growth, water absorption, and enzymatic activity. High concentration of Cr in plant tissue, particularly in leafy vegetables, also causes crop loss and contamination of food chains, these are kale, spinach, and mustard, with high heavy metal accumulation capacity (Saud et al.,2022).

Lead (Pb) is among the most widespread and well-documented of all environmental pollutants, with its source predominantly from industrial activities such as battery manufacturing, smelting and melting plants, paint booths, plumbing equipment, and municipal sewer system effluent (Jagetiya& Kumar,2020). Lead, after being released into the environment, is highly resistant to decomposition for years because it is not biodegradable and adsorbs tightly on soil particles, particularly clays and organic soils. Domestic and industrial effluent-contaminated sewage irrigation is the dominant channel of lead introduction into crop soils (Dongre, , 2021). lead is is hazardous to human health. As it can penetrate readily in the (BBB) blood-brain barrier and interfere with ontogenic normal development of the CNS (Collin et al.,2022). Literature shows that even low concentrations of lead can cause intellectual disability, behavior disorder, and attention deficit. Researchers also reported that chronic exposure to lead to anemia, hypertension, kidney damage, immunotoxicity, and reproductive toxicity. Similarly lead acts to calcium and also suppresses neurotransmission, bone metabolism, and enzymatic activities (Bansal, 2023). The World Health Organization (WHO) has declared there is no safe level of exposure to lead, especially in children. Lead-induced plant toxicity causes decreased photosynthetic capacity, disruption of water balance, inhibition of enzymes, and disruption of the cell membrane. It also causes chlorosis, curly leaf, shoot and root growth inhibition. (Rani et al.,2024). Lead also affects nutrient uptake and leads to nutritional disorders like iron and magnesium. High concentrations of lead in the edible portion of root vegetables and green leafy vegetables grown in lead-polluted soil, which directly affects the consumer. (Kumar et al.,2020).

Nickel (Ni) metal naturally present in the Earth's crust (Boyle et al.,2024). Nickel contamination of irrigating canals in agricultural regions primarily takes place due to industrial effluents, domestic effluents, and sewage sludge which all become a part of canal systems used for crop irrigation (Yu et al., 2022). Somehow, nickel can persist in water and land for easy uptake by plants, especially on sandy or acid soils (El-Naggar et al.,2021). In the human body, nickel is both a trace micronutrient required and a toxic compound when taken in excess. Long-term exposure to nickel may lead to dermatitis, respiratory disease, gastrointestinal distress, and immunological diseases (Mehri, 2020). Moreover, nickel sulfate and nickel chloride, and nickel salts (soluble) are human carcinogens (Group 1, IARC) and are also linked with lung and nasal cancers due to inhalation exposure. Furthermore, nickel has also been associated with nephrotoxicity (kidney damage), reproductive toxicity, and DNA damage since it can lead to the formation of reactive oxygen species (ROS) that disrupt cellular processes (Genchi et al.,2020). Plants nickel at high concentrations disturb normal physiological and biochemical activities. It delays seed germination, root growth, and chlorophyll production, resulting in inhibited photosynthesis and growth reduction. Nickel toxicity will also produce oxidative stress, membrane damage, and disruption of nutrient uptake iron and magnesium, most importantly leading to interveinal chlorosis and necrosis of the plant tissue (Altaf et al.,2022). Many researchers reported that nickel deposition into the edible portion is not only responsible for crop yield and quality decrease but also impacts the serious food safety of the population consuming these crops (Rizwan et al., 2024).

1.6 Problem Statement

The contamination of canal water in District Swabi has severe implications for public and vegetable health, and soil health. Tomatoes are ubiquitous in food systems where vegetable

consumption is concerned, and they are well-known hyperaccumulators of toxins from contaminated irrigation water. Consequently, consumers are exposed to toxic materials such as heavy metals. Pollution-induced loss of soil quality threatens public health through the food chain and has consequences for tomato yield and nutritional value.

1.7 Objectives

- To determine the chemical composition of canal water being used for irrigation in the study area.
- To assess the impact of canal water pollution on soil properties, including heavy metal concentration and other physicochemical parameters.
- To evaluate the uptake of contaminants (including heavy metals) by tomatoes irrigated with canal water, and the accumulation in the edible portions of the plant.
- To assess health-related risks associated with the consumption of contaminated tomatoes to the local community and elsewhere.

1.8 Significance of the Study

In agricultural areas, the problem of water pollution makes this research very important since it presents greater environmental and health risks. The canal water is the only source of irrigation in District Swabi. Therefore, any contamination in the canal water will impact efforts at some level. The study will inform the impact of contamination on soil health, tomatoes, and the sustainability of agricultural practices in the area by considering the types and levels of contamination present in that water. We have also assessed how consuming contaminated tomatoes can cause significant health issues among the area's residents, especially in areas where a large portion of the population relies on them for daily sustenance. This study aims to generate a comprehensive understanding of the threats to public health, agricultural safety, and water quality, thereby providing a foundation for evidence-based strategies to mitigate risks and support all stakeholders. The results of the completed project will provide local representatives and other decision-makers with meaningful information about why water management and pollution control are critical, even beyond benefits to agriculture. Together, this understanding can contribute to improving the long-term health and well-being of the community.

2. Literature Review

In Bahawalpur, Pakistan, Kaur et al. (2025) in their study analyze the accumulation of heavy metals in various vegetables irrigated with untreated wastewater. Heavy metal accumulation in soil and plants (specifically tomatoes) was examined for cadmium, chromium, lead, and nickel. They measured concentrations for the heavy metals in the vegetables and computed bioaccumulation factors. Results revealed that for TOMATO and a generic vegetable with sandy clay loam growing medium, accumulation factors for Ni, Cd and Cr were >1, thus indicating that substantial accumulation of heavy metals occurred. The health risk index values ranged from 0.313 to 0.515, thus they are for relative comparison SAFE; however, target hazardous quotient (THQ) values for all vegetables were >1, thus identifying a non-carcinogenic health risk for all vegetables based on the consumption of their vegetables. Claimed short term health risks may appear to be deemed acceptable; however, long term health risks associated with the latter may be minimized if these are known. They concluded that there should be a collective corrective response by local authorities to encourage prompt wastewater treatment now moving forward so these are not used for irrigation without treatment in the future.

Salem et al. (2024) evaluated the effectiveness of a variety of soil and wastewater remediation technologies against the safety of tomatoes produced in the contaminated environment in Egypt. The experiment employed a greenhouse trial at the National Research Center in Cairo and a field trial in El-Rahawy village with the treatments being rock phosphate, elemental sulfur, bentonite, phosphate-dissolving bacteria, and Thiobacillus sp. for the soil remediation, and a down-flow hanging sponge (DHS) system for the

treatment of wastewater. The findings showed the DHS system to be efficacious in the removal of potentially toxic elements (PTEs) in agricultural drainage water with 100% removal of cadmium, 93.3% of copper, 97.8% of manganese, and 77.8% of zinc. Moreover, the follow-up irrigation of the cleaned soil with the treated water was shown to decrease the concentration of the PTEs in the tomatoes by up to four orders of magnitude lower than detection limits for cadmium. The health risk assessments showed that the estimated daily intake and total hazard quotient (THQ) was less than acceptable levels in all of the treatments, and eating the tomatoes produced with the treated water posed no significant hazard to consumers. Also, it was concluded that the application for the remediation technologies can greatly reduce heavy metal contamination in tomatoes, and thus, for human use.

Aksouh et al. (2024) conducted a study of the heavy metal contamination in their irrigation water, soils, crops, specifically tomatoes (Lycopersicum esculentum L.) from the peri urban area of Boumerdes City, Algeria. The researchers collected irrigation water, soil samples and various fruits and vegetables that were subsequently analyzed for heavy metals (Cd, Cr, Cu, Fe, Ni, Pb, and Zn) by atomic absorption spectrometry. The authors stated that levels of heavy metals in the samples were generally below the WHO standards. However, analyses on health risk assessment indicated health risk in vegetables, health risk was determined through the hazard index (HI) and total target hazard quotient (TTHQ) analyses where dietary risk was determined, especially with eating vegetables. Specifically for tomatoes the transfer of Cd and Cu was considerable and the estimated daily intake values for indications of food safety or human health can be beneficial for continuous monitoring of food infrastructure where there might be heavy metal contamination present.

Mekonnen et al. (2024) conducted a comprehensive study in the Abuarie irrigation site, Northeast Ethiopia, to assess the health effects of potentially toxic metals including chromium, cadmium, iron, lead, copper, zinc and cobalt from agricultural soil, irrigation water, and tomato plants. The researchers collected samples from soil, irrigation water, and tomato plants, which were digested using the acid digestion method. The concentrations of PTMs were quantified using Inductively Coupled Plasma–Optical Emission Spectroscopy (ICP-OES). The levels of PTMs in the soil, tomato, and irrigation water samples ranged from 49,020 ± 275 (Fe) to 11.85 ± 0.44 (Cd) mg/kg in soil, 170 ± 1.98 (Fe) to 0.29 ± 0.006 (Cd) mg/kg in tomatoes, and 0.24 ± 0.003 (Fe) to 0.025 ± 0.005 (Ni) mg/L in irrigation water. The findings revealed that Zn, Ni, Cd, and Cr in soil; all metals in tomato; and Cu, Ni, Cd, and Pb in irrigation water samples were above the WHO Standards. Moreover, the separate and cumulative exposure to farm soil, irrigation water, and use of tomatoes were investigated using the hazard quotient (HQ) and hazard index values, The findings indicated that individual exposure to each sample type did not have a significant impact on health (HQ < 1). However, simultaneous exposure to all of the sample at the same time had a high likelihood of affecting health (HI > 1). The total carcinogenic levels of Cr, Cd, Ni, and Pb were higher than 1 × 10^−4, revealing that farmers have a high probability of developing cancer during their lifetime. The study recommends minimizing simultaneous exposure to soil, tomato, and irrigated water for local people to prevent the risk.

Hassan et al. (2024) carried out a comprehensive research project to determine heavy metal accumulation in crops such as tomatoes (Solanum lycopersicum) irrigated with various stages of textile dyeing wastewater (TDW). They performed a pot experiment in a randomized complete block design with three replications, with the five vegetables i.e. red amaranth, cauliflower, tomato, and radish irrigated with groundwater (T1) and seven stages of TDW (T2- T8). Lead, cadmium, chromium, and nickel concentrations were determined in the plant parts that are consumed. They found that higher levels of heavy metals in wastewaters leads to a higher accumulation of heavy metals in vegetables: T8, T7, T4, and T5 had the highest bio-concentration factor (BCF), estimated daily intake (EDI), target hazard quotient (THQ), and hazard index (HI) values

from other research to demonstrate the risk the vegetative crops pose to consumers. The study concluded that textile wastewater needs to be sufficiently treated before it can be safely used for irrigation in order to protect food commodities from heavy metal contamination.

Iqbal et al. (2024) collectively investigated heavy metal accumulation in vegetables (tomato (Solanum lycopersicum)) grown in peri-urban Multan City, Pakistan, that were irrigated with wastewater. The researchers collected 100 vegetable samples (30 soil; 30 water/wastewater) to measure cadmium, chromium, copper, manganese, nickel, and lead concentrations using Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES). Overall, the results illustrated that vegetables irrigated with wastewater accumulated heavy metals at levels that were notably greater than the vegetables irrigated with canal or tube well water. The accumulation factor range for vegetables irrigated with wastewater was 2.50 to 13.74, and the accumulation factor range for vegetables grown with other clean water sources was low (0.34 to 0.57). The total target hazard quotient (TTHQ) reflects health risk(s), even just from eating the vegetables. They concluded that wastewater irrigation is a major source of soil polluted with heavy metals; vegetables contribute to heavy metal toxicity, and that there needs to be treatment of wastewater before using for irrigated agriculture to reduce health risk(s).

Ahmed et al. (2023) evaluated the impact of hazardous heavy metals on the growth and safety of tomatoes irrigated with treated wastewater, in Egypt, Two main study areas were used: a control area irrigated with Nile river tributary water and a contaminated area irrigated with raw (untreated) industrial wastewater. Results showed significant reductions in key soil and plant nutrients (N, P, K) in addition to significant recoveries of toxic metals (Cd, Pb, Fe, Mn, Ni) in soils and tomato plants ($p < 0.001$) with contaminated wastewater irrigated treatments. Bioaccumulation factors (BF) when exceeded 1 for most metals in root systems, indicating the plant transported high levels of toxic metals, while translocation factors (TF) exceeded 1 for Pb and Ni in the shoots showing that toxic metals moved into the edible parts. Overall, tomato fruit tissue concentrations of Fe (5000.1 mg/kg), Pb (360.7 mg/kg), and Mn (356.3 mg/kg) is notable. A health risk assessment indicated daily intake rates (DIR) and hazard quotients (HQ) were also elevated like those for Pb (HQ: 2073.8 adults, 2558.9 children), Cd (HQ: 574.0 adults, 708.3 children), and Fe (HQ: 41.1 adults, 50.7 children) which may severely compromise human health. In conclusion, this research study suggests that growing tomatoes and irrigating with untreated wastewater irrigation poses serious health hazards to human health and should not be used for human consumption.

Tabassam et al. (2023) investigated heavy metal bioaccumulation in tomato fruits (Lycopersicon esculentum L.) grown from wastewater treatment in Faisalabad, Pakistan. They obtained tomatoes from cultivated fields with crops receiving untreated wastewater and assessed heavy metals using Atomic Absorption Spectrophotometry and listed the concentrations of the heavy metals. The study's findings showed that tomatoes produced with wastewater irrigation had much higher metal concentrations than tomato samples grown with clean water. Such as got over the maximum residue limit of Cadmium and lead above this specified in multiple international food safety standards. The authors concluded that tomatoes grown with contaminated water, including heavy metals, posed an unacceptable health risk to consumers, and the need exists for wastewater to be treated for irrigation and to be monitored.

Alam et al. (2023) studied the impact of untreated industrial wastewater on tomato crops in South Cairo, Egypt. They identified two study locations where one was irrigated with safe Nile water (control), and the second was fertilized with raw industrial wastewater (contaminated location). They will collect soil samples and tomato plants from each location to identify nutrients and toxic metals with the Atomic Absorption Spectrophotometry. The study found significant deficits in the essential nutrients (N, P, K) but also severe contaminants of heavy metals such as total Pb (360.7 mg/kg), total Fe (5000.1 mg/kg), and total Mn (356.3 mg/kg) in edible fruits. The bioaccumulation factors (BF > 1) indicated that

the metals moved to roots, while the translocation factors (TF > 1) indicated where Pb and Ni accumulated in the shoots. The study recorded daily intake rate (DIR) and hazard quotients (HQ), which were significantly likely to exceed national safe limits with respect to both adults and children. The study concluded that tomatoes contaminated by this water source were unsafe for human consumption and presented very serious health hazards, including chronic toxicity and developmental danger to children.

In the article written by Barua et al. (2023) investigated the Export Processing Zone in Bangladesh for heavy metals bioaccumulation in the soil, irrigated water, and tomato (Lycopersicon esculentum) vegetables. The authors collected samples from the irrigated water, soil, and the tomatoes being irrigated (fruit, roots, shoots, leaves, and total fruit weight (green and ripe tomatoes). The authors determined using acceptable analytical methods the levels of heavy metals (i.e., cadmium, chromium, lead, and nickel. The results show a different accumulation of Cd, Cr, and Pb in tomato plants and higher concentrations of each of these metals and plant shoots and green tomatoes (i.e., unripe fruit). The authors also indicated the accumulation of Ni was principally in the roots with low concentrations in the ripe tomatoes. The authors indicate consumer health neglect in regards to bioaccumulated heavy metals on the various parts of the tomato plant and indicate caution should be considered for irrigation in this area.

Heavy metals were detected in fruit and vegetables in the Solapur region of Maharashtra, India according to Mawari et al (2022). Authors looked at lead (Pb), cadmium (Cd), arsenic (As), and mercury (Hg) in 24 variety of fruit and vegetable samples. The authors used Inductively Coupled Plasma - Mass Spectrometry (ICP-MS) to quantify their samples and found lead (Pb) to have the greatest calculated value (0.17 ± 0.38) follow by arsenic , cadmium, and mercury. They reported the highest heavy metal findings were in tomatoes and garlic. The authors were understanding that vegetables had higher concentrations than fruit and some vegetables presented some serious health risk based on Metal Pollution Index and Health Risk index scores.

Berihun et al. (2021) examined the level of contamination of heavy metals in vegetables, soil, and irrigation water of Keha canal farms from Gondar, Ethiopia. Flame atomic absorption spectrometry was used in the study to analyze concentrations of Cu, Mn, Zn, Cr, Cd, Ni, and Pb in Ethiopian kale, cabbage, Swiss chard, lettuce, onion, tomato, and potato. Outcomes indicated the mean level concentrations of Cadmium (0.23–6.25 mg/kg), Ni (7.41–51.85 mg/kg), and Pb (0–9.52 mg/kg) in vegetables were above WHO/FAO acceptable limits. Leafy greens, particularly Swiss chard and Ethiopian kale, were found to contain the highest level of contamination. Soils also contained higher levels of Pb (138.09–259.24 mg/kg), Ni (85.18–259.26 mg/kg), and Cd (4.63–20.37 mg/kg), above FAO limits. In addition, irrigation water comprised Cr (0.5 mg/L), Cd (0.046 mg/L), and Cu (1.80 mg/L) in excess of US EPA standards. Their research determined that ingestion of vegetables cultivated in this region has possible chronic health impacts, particularly due to greater bioaccumulation of heavy metals in leafy vegetables.

Ishaq et al., (2020) performed a research study to investigate the concentrations of pesticide pollutants and heavy metals in tomato plants, irrigation water, and soil in Peshawar City. The results confirmed that the pH, total dissolved solids (TDS), and electrical conductivity (EC) of the sewage water were significantly higher than the recommended allowable limits of the World Health Organization. There were higher concentrations of lead, nickel, copper, zinc, and iron in the sewage water and the soils used for growing tomatoes. In addition, the pesticide residues, amectin and chlorpyrifos, were above the European Union (EU) recommended acceptable percentages in the lysate of tomato fruits, leaves and soil. With special attention to the urgent need to monitor pollution in sewage water-irrigated tomatoes, the present study aims to safeguard consumer health.

Ishaq et al. (2020) studied heavy metal and pesticide contamination in tomato crops harvested in Mansehra, Pakistan. The authors

took soil and fruit samples from farms to evaluate heavy metal and pesticide leftovers by using canal water, tube well water and wastewater. Using atomic absorption spectrophotometry and gas chronicography of these samples the authors surprised to find that tomatoes grown with wastewater had significantly higher cadmium (Cd), lead (Pb) levels than canal water and tube well water irrigation; in some cases, the levels surpassed the international food safety level. They concluded that contaminated grown tomatoes are a serious health risk, and they recommended monitoring the actual water and soil, monitoring crops, and irrigating only with less hazardous irrigation methods.

Naz et al. (2020) examined the effect of sewage water irrigation intervals on the growth, yield, and heavy metals accumulation in tomato (Solanum lycopersicum) and okra (Abelmoschus esculentus) at Bahauddin Zakariya, University Multan, Pakistan. Farmers have been making continuous use of sewage water for irrigation without treatment. In the experimental design there are different irrigation intervals (5, 10, and 15 days) and four samples of the soil and tomatoes (and okra) were taken for each irrigation frequency. Each of the samples was tested for Cd, Pb, and Ni concentration via atomic absorption spectrophotometry. The results indicated that by using sewage water more frequently (every 5 days) led to a higher level of heavy metals in the soil and the plant tissue, while applying sewage water every 15 days led to a significantly lower concentration. The yield and growth of the tomato and okra increased with irrigation frequency, however, the yield and growth of the tomatoes and okra whereby the edible parts of the plant showed high levels of heavy metals elevated concerns regarding food safety. The authors concluded that sewage water irrigation may improve growth and yield, however, when used without proper management and treatment pose health issues due to heavy metal contamination.

Pajević et al. (2018) reported heavy metal concentrations in vegetables that are considered disgusting by humans, and reported the association between the location of the plant contamination and growth. They collected vegetable samples over the period of a 4-year survey from the small farms surrounding their community in Serbia's Vojvodina Province, encompassing 11 commonly grown vegetables. The findings indicated that high levels of lead , cadmium, nickel, and chromium was found in a number of the vegetables included in their study. Most of the Cd accumulation was found in spinach with more than 54% of snack samples with Cd concentrations above the maximum permissible concentrations (MPCs) and 46% of snack vegetables with Pb levels over the allowable limits. Notably, all vegetables contained Cr concentrations below the FAO/WHO guideline level and spinach contained the most Cr, followed by parsnips and sugar beet. The plain tomatoes and broccoli had the second most mean Ni content (after spinach) compared to the other snacks. The authors concluded that it is essential to continuously monitor heavy metal concentrations in vegetables to protect public health.

Zakir et al. (2016) examined the quality of water from the Tongi canal of the high population and fast-urbanizing north Dhaka in Bangladesh. Data collection involved sampling 26 samples to analyze trace metals and bulk ionic contents. The researchers detected iron, manganese, zinc and lead with Atomic Absorption Spectrophotometry at varying concentrations, and Pb concentrations were found to be comparatively high in the range 0.43 to 0.64 µg/mL. Additionally, the major ions calcium, magnesium, sodium, potassium, bicarbonates, chlorides, borates, phosphates, and sulfates were also quantitated. The findings indicated that the majority of the samples were unsuitable for irrigation in terms of high bicarbonate (HCO_3^-), sulfate (SO_4^{2-}), phosphate (PO_4^{3-}), and potassium (K^+) concentrations. Interestingly, 96% of samples were not suitable according to residual sodium carbonate (RSC) and 92% of the samples were defined as hard water. They pointed out the prime need for continuous monitoring and contamination control, specifically for Pb content, in order to avoid prolog agricultural and ecological harm.

Sohag and Syed (2014) stated that the Phuleli Canal is one of Hyderabad's main sources for

drinking water and irrigation, has been assessed and is very polluted. The study discusses the implications of widespread encroachment along the canal banks, domestic sewage, and industrial effluent and as a result the water quality is severely impaired.

Field studies showed multiple solid waste and sewage dump sites along the canal banks that discharges pollutants into the canal. Laboratory analysis confirmed that heavy metals were present and that other impoundments were greatly contaminated both above safe levels, based on WHO recommendations. It is evident, that, fecally contaminated canal water, a major cause of diarrheal disease in Pakistan, has significant public health implications. The authors felt that the area could be cleaned up considerably especially if effective control of all encroachments, as well as cleaning up the waste disposal units could be undertaken as soon as in order to save public health and water quality.

Farrag et al. (2016) carried out a study to assess the concentration and translocation of heavy metals namely cadmium, chromium, copper, lead, nickel, and zinc in wastewater-irrigated soils and food and feed crops (such as cabbage, onion, tomatoes, garlic, wheat, fava bean, peppermint, and clover) grown along the El-Saff wastewater canal in southern Giza, Egypt. Although the physicochemical characteristics of wastewater and soils were generally in the WHO standards, the heavy metal contents were quite different among crop species. Zn and Cu showed maximum accumulations, with the general concentration order in edible tissues being Zn > Cu > Ni > Cr > Cd > Pb. Significant translocation was observed for Zinc, Nickle, in fava bean; Cadmium in garlic; Chromium in peppermint; and Pb in fava bean and onion. While the majority of metal concentrations were lower than health hazard levels except for Cr and Ni the research emphasized the need for routine monitoring because of possible long-term health effects for humans and livestock consuming these crops.

Materials and Methods

3.1 Study area:

Swabi District is located at 34°7' N latitude and 72°28' E longitude. District Buner borders it to the north, District Haripur borders it to the east, District Attock borders it to the south, and Nowshera and Mardan Districts border it to the west (Gul, 2022). The region is elevated between 300 and 650 meters above sea level, with an average elevation of roughly 321 meters. According to Shah et al. (2022), the area's greatest temperature is 45.5°C in June and its lowest is 2°C in January.

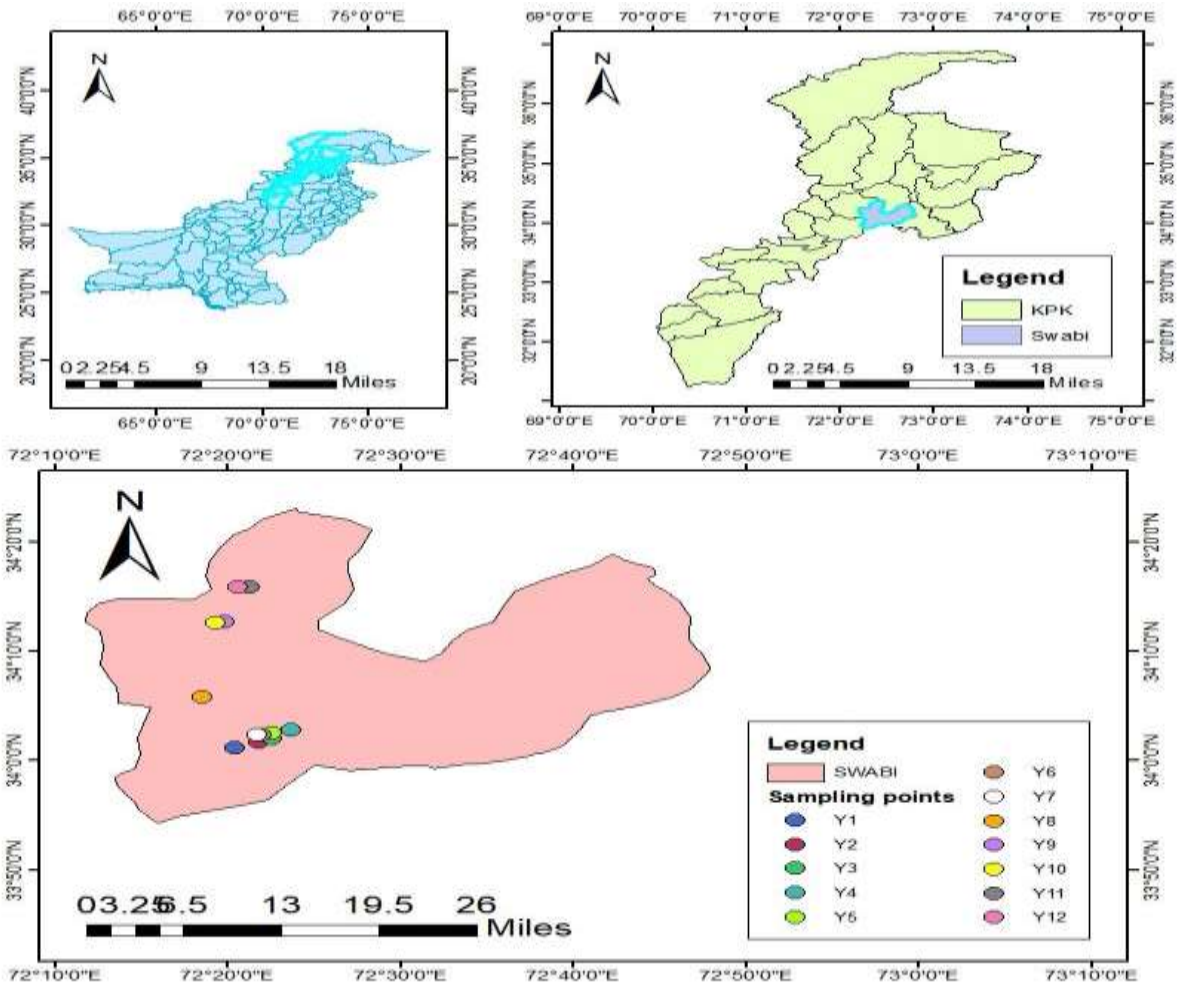


Figure 3.1. Map of the study area showing the sampling point

3.2 Population of study area

The below table (3.1) showing the population of study area:

S. No	Attribute	Description
1	District Established	1988
2	Total Area	1,543 km²
3	Population (2023)	~1.89 million
4	Tehsils	4 (Swabi, Razar, Lahore and Topi)
5	Union Councils	56
6	Village/Neighborhood Councils	~160
7	Major Language	Pashto (97.2%)
8	Literacy Rate	58.5% overall (M: 72.3%, F: 44.5%)

(Source: Pakistan Bureau of Statistics 2022)

3.3 Historical and Cultural Significance

Table (3.2) showing the Historical and Cultural Significance of the study Area:

S. No	Attribute	Description
1	Yousafzai Tribe	Swabi is predominantly inhabited by the Mandanr branch

2	Gaju Khan Baba	Respected tribal chief with a shrine in Swabi
3	Ranigat Buddhist Ruins	Located on the Swabi-Buner border
4	Hund Museum	Showcases ancient Gandhara civilization

(Source: Pakistan Bureau of Statistics 2022)

3.4 Edaphology

District Swabi contains different soil types because it consists of alluvium and loess deposits. The soil texture of the study area ranges from sandy to loamy. On the other hand, the soil textures derived from the loess plains are mostly silty clay-loam to silty loam (Anwar et al., 2021).

3.5 Hydrology

Surface water bodies in Swabi district include ponds, streams, canals, drainage ditches, and marshy areas, which cover 2.41% of the total area of the district (Government of Pakistan, 2000). Most of the land drainages are torrents, referred to in the local language as Khwar. The primary irrigation source in Swabi is the Lower Swat Canal, which runs across the plain areas. In contrast, the steep regions are mostly dependent on rainfall because of the difficult entry levels made possible by the canals. (Anwar et al., 2021).

3.6 Natural Vegetation

Spinach, bottle gourd, cabbage, carrot, Colocasia, tomato, cucumber, potato, red pepper, cauliflower, turnip and lettuce, etc. are grown in the district (Ali et al., 2021). Wheat, maize, fodder plant, garlic, rice and potato are the principal crops grown here (Ahmad et al., 2021). *Nicotiana tabacum* is the principal cash crop of district Swabi (Sattar et al., 2020). In Swabi, tall tree forests constitute approximately 0.7% of the land, shrubs and bushes cover almost 10.4% and rangelands comprise 14.5% (Government of Pakistan, 2014). Acacia modesta and *Ziziphus mauritiana*, which are dominant in the tropical shrub and sub-tropical forests. *Dodonaea viscosa* is the main distinguishing plant of scrub forests (Anwar et al., 2021).

3.7 Sample Collection and Preparation

3.7.1 Water sampling

The sample sites for this study include agricultural fields from several villages of Swabi where canal water is the primary source of irrigation. These villages are Maneri Payan, Maneri Bala, Ismaila, Shewa, Kalu Khan, Swabi Khas, Saleem Khan, Zaida, Gohati, Dobian, Yar Hussain, Yaqubi, Jaganath, and Chota Lahor. These sites were selected because they heavily depend on canal irrigation for tomato cultivation and are vulnerable to contamination from sewage and domestic waste.

Canal water samples were taken systematically from the sampling sites in Swabi that represent the upstream, midstream, and downstream sections of the canal (Abdel et al., 2020). The basis for this spatial distribution was to take into action the possibility of variations in contamination levels due to different types of contamination through residential discharges, agricultural discharges, and industrial waste discharges. Clean and sterilized polyethylene bottles were used in order to eliminate the potential for chemical reactions or contamination (Bharti et al.,2022). Each sample bottle was clearly labeled (Cando et al.,2023). Once the samples were obtained, the sample bottles were sealed immediately to reduce the potential for contamination (Panhwar et al., 2022). All samples were kept in portable coolers and held at low temperature (about 4°C) during transport to the laboratory to maintain their physico-chemical status. Nitric acid was used to preserve the samples (stabilization of heavy metals). To verify the traceability and authenticity of the results for the collected samples, appropriate safety protocols were adhered to during sample collection and transportation. (Tripathi, 2024).

3.7.2 Collection of Soil Samples

To assess the quantity of the contaminants, samples of soil were collected at two depths (0 to 15 cm and 15 to 30 cm) in areas irrigated with canal water (Yu et al.,2022). A stainless-steel soil auger and trowel were used to collect soil samples.

Special care was taken to avoid contamination by any materials that could affect the sample quality. Each sample was immediately stored in sealable plastic bags, and then the samples were taken to the laboratory. Then the samples were air-dried at room temperature in trays in a clean dust dust-free area. Once dried adequately, the sampled soils were passed through a 2 mm mesh sieve to avoid larger material (Newman & Fourie, 2023). For the chemical and physical analysis, sieved samples were grinded into a fine powder to a specific grain size using a mechanical grinder. The samples were then ready for further analysis (Bottomley et al., 2020).

3.7.3 Tomato Sampling and Preparation

Samples of tomato fruit were collected from the crops irrigated with CWIS (canal water-irrigated-soil). Clean scissors were utilized to collect the samples, which also eliminated contamination from soils or other plant materials. Collected samples were placed in sterile labeled plastic bags, which provide adequate tracking and identification (Ahmed et al., 2023). As soon as the samples were collected, each sample was cleaned with distilled water to avoid any soils or dust that had adhered to the surface. The samples were oven dried at a temperature of 60°C while the plants were powdered with a mortar and pestle. The powdered samples were stored in airtight containers in cool and dry conditions until they were analyzed (Salem et al., 2020).

3.7.4 Water samples Preparation and analysis

Before the water samples could be analyzed, suspended solids were removed by filtering them through Whatman filter paper to eliminate any particles that could affect analysis using AAS. After filtering, samples were acidified with concentrated nitric acid in order to medium all the metals in the sample and stabilize the sample, preventing any loss of concentration of the metal ions due to chemical reaction or microbial metabolites induced from storage (Fitriani et al., 2023). The acidified samples were stored in new, cleaned polyethylene bottles at 4°C until analysis took place. For the heavy metals analysis, the acidified samples were analyzed using Atomic Absorption Spectroscopy (AAS), an analytically sensitive and accurate analytical technique that is highly desirable when quantifying trace levels of metallic elements (Hee et al., 2022). The metals were chosen based on prevalence in wastewater, and their alleged toxicity and bioaccumulation potential (Goh et al., 2020).

3.7.5 Soil Samples Analysis

For the digestion, concentrated hydrochloric acid (HCl), nitric acid (HNO_3), and hydrofluoric acid (HF) were added to the samples in the ratios of 3:1:1 (HCl: HNO_3:HF). This equal combination of acids allowed for the breakdown of silicate minerals and the release of bound heavy metals that are contained within the soil. The digestion process was operated under a controlled process until complete digestion was accomplished. The soil sample underwent filtration through a filter paper after digestion was completed to remove any residual suspended particles, only leaving the dissolved fraction for further analysis (Peng et al., 2021).

3.7.6 Tomato Samples Analysis

After drying and grinding the tomatoes fruit materials an acid digestion (Nitric acid (HNO_3), Hydrochloric acid (HCl), perchloric acid ($HClO_4$) was performed on the plant matrix to extract heavy metals (Gong et al., 2020).) to decompose organic tissue and extract. Once the digestion was completed, the digest was filtered to remove particulates, which resulted in a clear extract. The clear extract was diluted with distilled water and then analyzed by Atomic Absorption (AA) spectrophotometry to quantify heavy metals: lead, cadmium, and Ni in plant tissues (Abubakar et al., 2020).

3.8 Health Risk Analysis

3.8.1 Estimated Daily Intake (EDI)

Estimated Daily Intake (EDI) is an important parameter in health risk assessment. It allows for the calculation of how much of a contaminant (e.g., a heavy metal) an individual ingests daily through food (e.g., tomatoes) contaminated with that substance. The estimated daily intake is used

to compare an individual's intake against safe levels set by health agencies, such as the WHO and USEPA standards. Estimated Daily Intake (EDI) can be calculated using the formula.

$$EDI = \frac{C \times IR \times EF \times ED}{BW \times AT} \quad \text{eq (1)}$$

Where, C = Concentration of metal in the edible part of the plant (mg/kg)
IR = Ingestion Rate (kg/day)
EF = Exposure Frequency (days/year)
ED = Exposure Duration (Years)
BW = Body Weight (kg)
AT = Averaging Time (days)Geo-Accumulation Index (Igeo)
The Geo-Accumulation Index was calculated using the following equation (Łyszczarz et al.,2020).

$$Igeo = log2\,(Cn / K.Bn)$$

eq. (2)

Where:
Igeo= Geo-Accumulation Index
Cn= Concentration of metals in the samples
Bn= Background concentration of the metal

3.8.3 Transfer Factor Formula

The Transfer Factor was calculated using the following equation (Susanto et al.,2023).

$$TF = \frac{C\ soil}{C\ vegetables}$$

eq. (3)

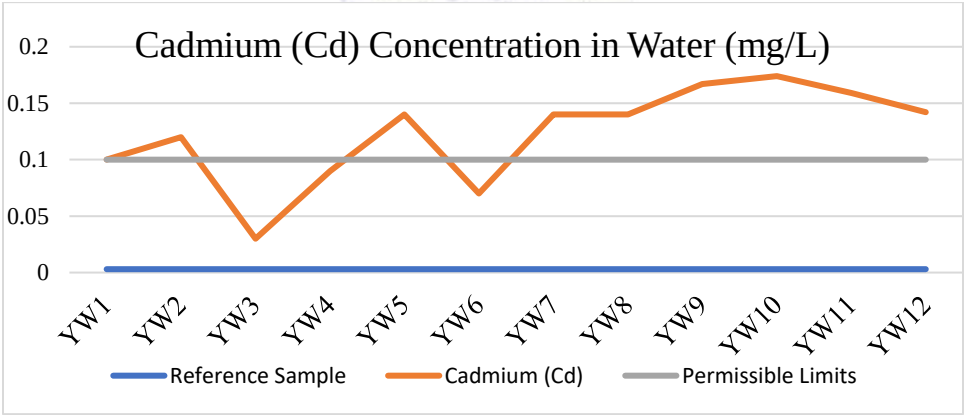
Where:
TF = Transfer Factor
C plant = Concentration of contaminant in the plant
C soil = Concentration of contaminant in the soil.

4. Results and Discussion

This section describes the outcomes from the assessment of water, soil, and tomato samples taken from the study area. It will provide results concerning the concentration of heavy metals and other essential parameters compared to permissible limits to assess their environmental and health impacts. The data is presented in tables and figures to clarify differences observed and to better visualize the variations and trends among sample types.

4.1 Water Samples Results

4.1.1 Cadmium

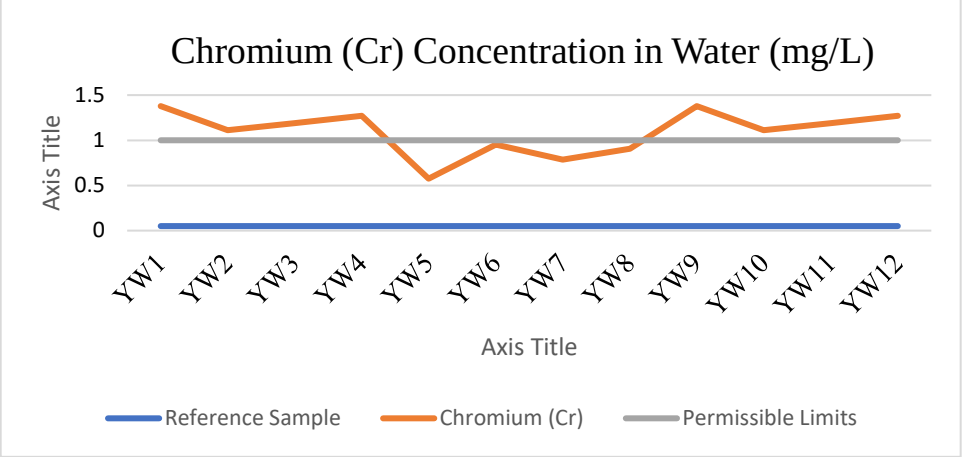


(Fig. no. 4.1.1 Showing the Cd Concentration in Water Samples)

The figure shows cadmium (Cd) concentrations for canal water samples (YW1 - YW12) were observed above the reference value (0.003) and the WHO standards of 0.1 mg/L. Higher values were documented for YW2 - 0.12 mg/L; YW5 - 0.14 mg/L; YW7 - 0.14 mg/L; YW8 - 0.14 mg/L; YW9- 0.167 mg/L; YW10 - 0.174 mg/L; YW11- 0.159 mg/L; YW12- 0.142 mg/L. The highest concentration was recorded for a water sample, YW10, which was 74% higher than the limit. Therefore, all samples showed that cadmium concentrations are a health hazard if the untreated water is utilized for the irrigation purposes of crops. In contrast, YW3 and YW4 < 0.1 mg/L and

YW1 was equal to the threshold value. The graph shows that most of the water samples tested were contaminated by cadmium. This is a potential environmental and health hazard.

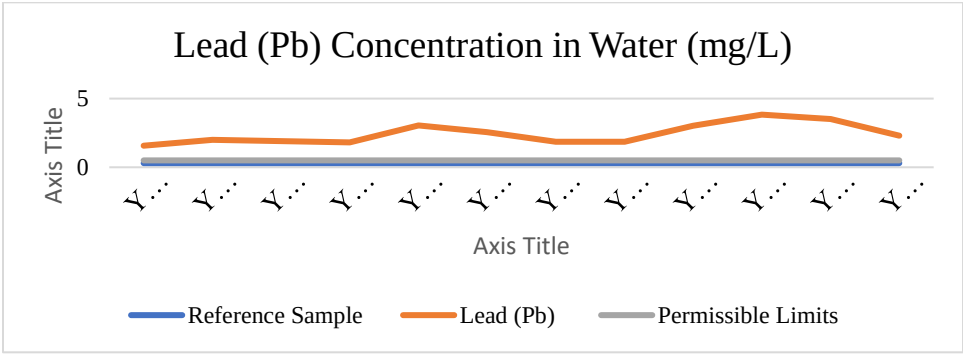
4.1.2 Chromium



(Fig. no. 4.1.2 Showing the Cr Concentration in Water samples)

Almost all of the water sample combinations from chromium (Cr) levels presented in the graph (YW1 - YW12) have levels above the reference value (0.05) and also above the WHO standards (1 mg/L). The samples with the highest concentrations of Cr are YW1 and YW9 (1.378), YW4 and YW12 (1.271), YW3 and YW11 (1.189), YW2 and YW10 (1.112). Each of them is above the threshold of contamination. The following samples show acceptable levels for Cr levels YW5 (0.575), YW6 (0.953), YW7 (0.787), and YW8 (0.906). The graph clearly depicts a trend for the samples, indicating high levels of chromium, which raises serious concerns regarding the salinity of water for irrigation, and heavy metal accumulation in soils and crops.

4.1.3 Lead

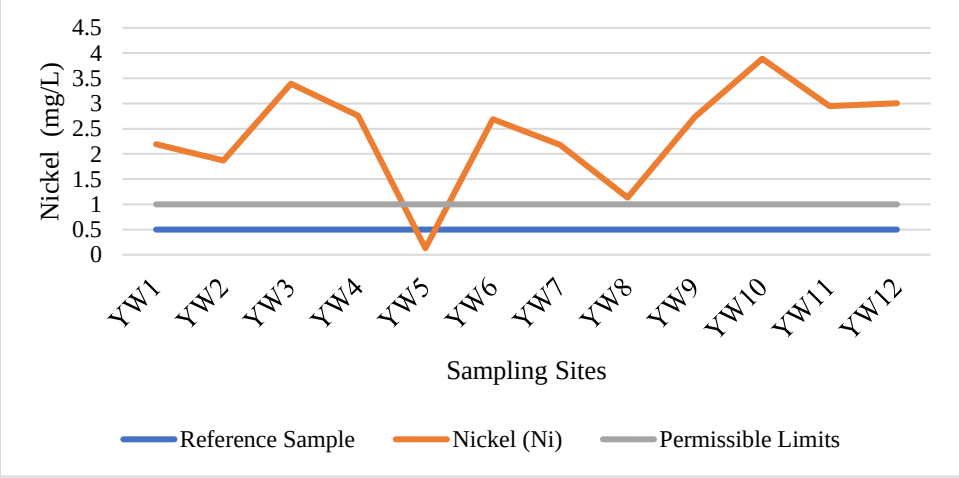


(Fig no. 4.1.3 Showing the Pb Concentration in Water Samples)

This figure illustrates the concentrations of lead in the canal water samples taken from the study area. The analysis indicated that all the samples had the level of Pb well above the reference values (0.3 mg/L) and also above the WHO standards of 0.5 mg/L, indicating a state of elevated contamination. The lead concentrations were highest when measuring sample YW10 (3.83 mg/L), YW11 (3.52 mg/L), YW5 (3.04 mg/L), and YW9 (3.01 mg/L), all of which were above the standard. Some other samples, YW6 (2.55 mg/L), YW2 (2.00 mg/L) and YW3 (1.90 mg/L) were recorded to have some concentrations of lead as well. The levels of Pb in

the lower range of our findings, including YW1 (1.57 mg/L), YW7 (1.85 mg/L), and YW8 (1.85 mg/L) were once again lower values but still above permissible levels. Therefore, the use of this water from an irrigation perspective presents a significant risk because of such high lead levels in the context of the potential for lead accumulation in the soil, crops and food value chain, adding risk to both ecosystems and human health.

4.1.4 Nickle

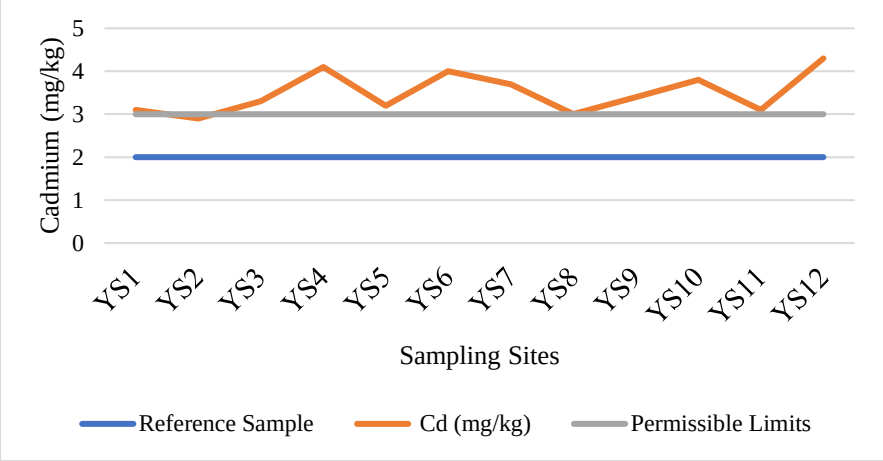


(Fig no. 4.1.4 Showing the Ni Concentration in Water Samples)

The figure highlights nickel (Ni) concentrations in canal water samples, in which most concentrations are above the reference value (0.5 mg/L) and also exceed the WHO standards of 1.0 mg/L. Of the samples collected, the highest concentration was observed in YW10 (3.887 mg/L), followed by YW12 (3.004 mg/L), YW3 (3.394 mg/L), and YW11 (2.947 mg/L). Other samples such as YW4 (2.756 mg/L), YW9 (2.729 mg/L), and YW6 (2.689 mg/L) also recorded values more than double the safe limit. Only YW5 recorded the lowest concentration at 0.13 mg/L, which was within the safe range, whereas 11 out of 12 samples exceeded permissible levels, indicating widespread contamination of the canal water. The elevated Ni levels may be attributed to multiple potential sources, including industrial effluent discharges, municipal sewage inflows, and solid waste dumping sites located near the canal system (Shah et al., 2019; Ali et al., 2021). Previous studies in Khyber Pakhtunkhwa have reported similar contamination trends, where untreated industrial wastewater and agricultural runoff were identified as major contributors of heavy metals in irrigation canals (Khan et al., 2020). Therefore, the elevated Ni concentration observed here likely reflects anthropogenic inputs, posing significant risks to soil stability, crop safety, and ultimately human health through long-term bioaccumulation.

4.2 Soil Samples Results

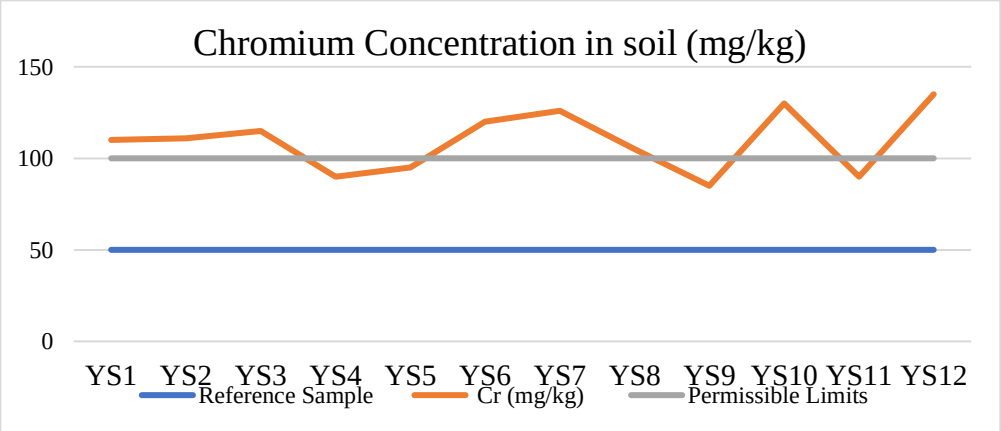
4.2.1 Cadmium



(Figure No. 4.2.1 Showing the Cd Concentration in Soil samples)

The above figure shows the concentrations of Cadmium (Cd) in the collected and monitored soil samples (YS1–YS12) of the study area. The reference value for Cd in soil was 2mg/kg. According to the WHO standards, the concentration of Cadmium in the soil shouldn't exceed 3 mg/kg (which is the allowed limit for Cd). However, findings of the current study depicted that the level of Cadmium in the soil samples ranged from (2.9 mg/kg to 4.3 mg/kg). The findings further show that the level of cadmium in the soil samples of the study area exceeded the WHO standards in all the soil samples except YS2. Sample YS12 had the highest levels of Cd at 4.3 mg/kg; samples YS4 at 4.1 mg/kg and YS6 at 4.0 mg/kg had the next highest concentrations. Only samples YS2 at 2.9 mg/kg and YS8 at 3.0 mg/kg had acceptable contaminant levels. The findings also indicate that the soil of the study area shows great potential to be contaminated with Cd. Which can ultimately damage the health of plants grown nearby and can pose a harm to human and food safety.

4.2.2 Chromium

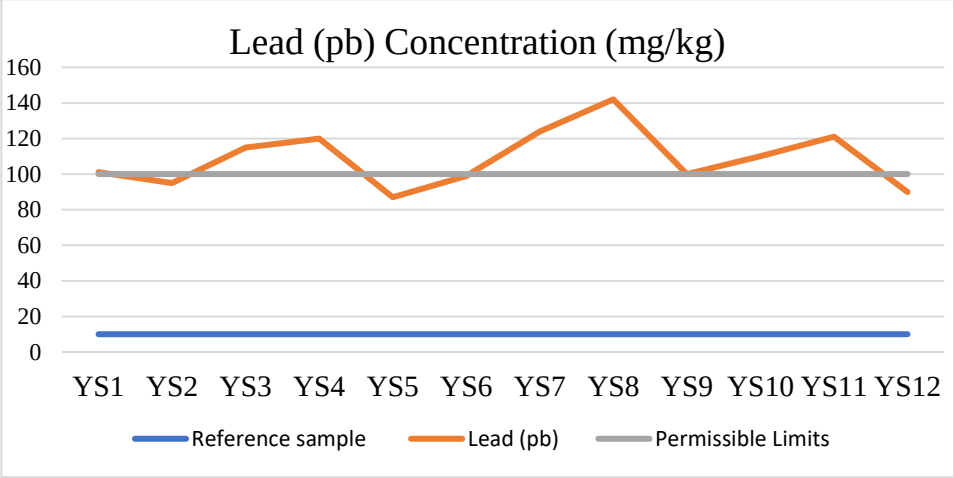


(Figure No. 4.2.2 Showing the Cr Concentration in Soil samples)

The figure shows the levels of Chromium in soil samples (YS1-YS12) in which the results exceed the reference value (50 mg/kg) and also above the WHO standards \of 100 mg/kg. The results indicate that most of the samples exceeded this allowable limit. The concentrations of Chromium range from 85 mg/kg to 135 mg/kg, where YS12 (135 mg/kg), YS10 (130 mg/kg), and YS7 (126

mg/kg) provided the greater concentrations of chromium. Soil samples YS4, YS5, YS9, and YS11 contained allowable limits for Cr detection. While the exceedance of Cr concentrations did not rise to a regulatory concern, it does point to potential anthropogenic contamination that results from wastewater and other sources.

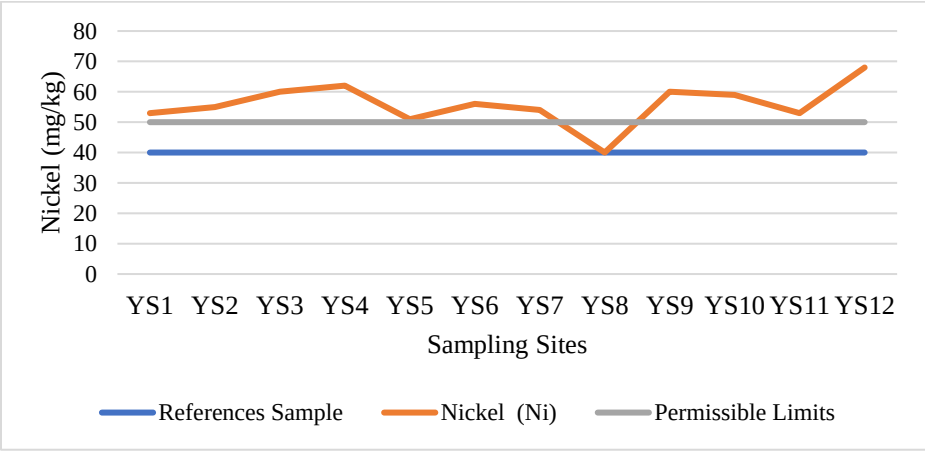
4.2.3 Lead (Pb)



(Figure No. 4.2.3 Showing the Pb Concentration in Soil samples)

The figure shows that the concentration of Lead (Pb) in soil samples (YS1—YS12) was above the Reference value (10mg/kg) and also exceeded the WHO standards of 100 mg/kg. The samples show that 80% of the samples exceed the recommended safety limit, and they range from 87 mg/kg to 142 mg/kg. Two samples followed suit, one at a Pb level of 124 mg/kg in YS8 and the other with a Pb level of 121 mg/kg in YS7. Only YS2, YS5, YS6, and YS12 found safe. The report states that high Lead concentration could pose a risk of soil contamination, which would have implications for plant life in terms of growth, food value, safety, and human health from long-term exposure (reference).

4.2.4 Nickle (Ni)



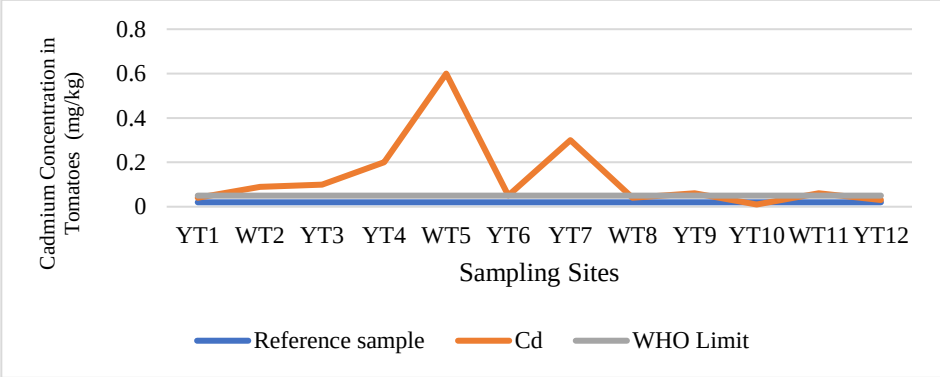
(Figure No. 4.2.4 Showing the Ni Concentration in Soil Samples)

The above figure shows concentrations of Nickel (Ni) from soil samples (YS1-YS12) that exceed the reference value (40 mg/kg) and also above the WHO standards of 50 mg/kg. Nickel levels in the

samples have ranged from 40 to 68 mg/kg. Most of the soil above the WHO standards of 50 mg/kg of Nickel and sample YS12 had the highest concentration of Nickel (68 mg/kg), while only one sample (YS8 at 40 mg/kg) was below the permissible limit. The overwhelming presence of Nickel across most soil samples raises concerns about soil contamination and crop quality (which may affect soil fertility). Ultimately, this issue may expose human health to increasing or excessive levels of Nickel in the food chain.

4.3 Tomatoes Samples Results

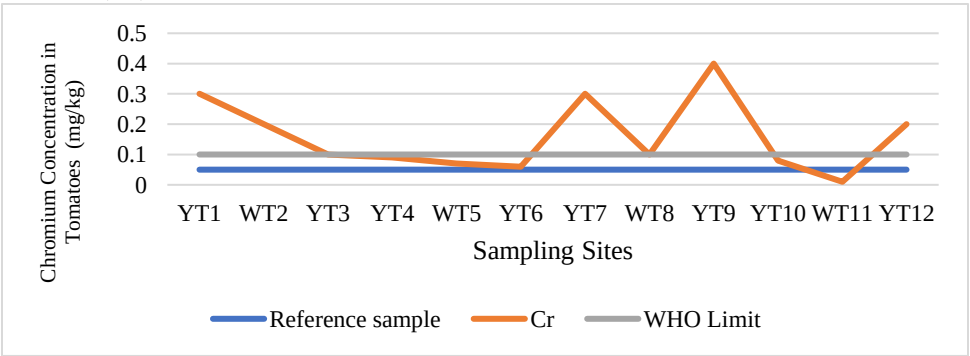
4.3.1 Cadmium (Cd)



(Figure No. 4.3.1 Showing the Cd Concentration in Tomato samples)

The figure shows that cadmium (Cd) concentrations in tomato samples exceeded the reference value (0.02 mg/kg) and also above the WHO standards (0.05 mg/kg). The values were observed as WT2 (0.09 mg/kg), YT3 (0.1 mg/kg), YT4 (0.2 mg/kg), WT5 (0.6 mg/kg), YT7 (0.3 mg/kg), YT9 (0.06 mg/kg), and WT11 (0.06 mg/kg). Some samples such as YT1 (0.04 mg/kg), WT8 (0.04 mg/kg), YT10 (0.01 mg/kg), and YT12 (0.03 mg/kg) were observed below the permissible limit. The cadmium levels exceeding the WHO threshold are of particular concern because they indicate possible contamination pathways, such as the use of polluted irrigation water or cadmium-enriched soils, leading to its bioaccumulation in edible crops (Rizwan et al., 2017and Khan et al., 2018). Therefore, this poses a potential health risk for consumers, especially with long-term exposure, as cadmium is a known toxic metal with cumulative effects on human health.

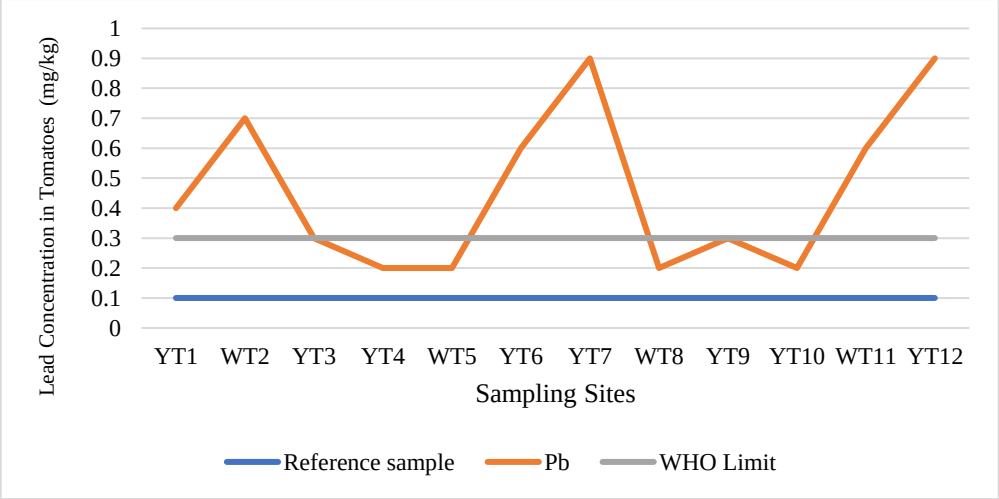
4.3.2 Chromium (Cr)



(Figure No. 4.3.2 Showing the Cr Concentration in Tomato Samples)

The data indicate that concentrations of chromium (Cr) in certain tomato samples found above the Reference value (0.05 mg/kg) and the WHO standards (0.1 mg/kg). The samples with elevated chromium concentrations in figure (4.3.2) were YT1 (0.3 mg/kg), WT2 (0.2 mg/kg), YT7 (0.3 mg/kg), YT9 (0.4 mg/kg), YT12 (0.2 mg/kg) with YT9 had the higher value Cr four times above the allowable limit where as YT4 (0.09 mg/kg), WT5 (0.07 mg/kg), YT6 (0.06 mg/kg), YT10 (0.08 mg/kg) and WT11 (0.01 mg/kg) had lower chromium concentrations. It is very alarming to find chromium in the edible portion (fruit) of tomatoes at higher than the allowable limit, as it may have serious health implications after some time of excessive consumption.

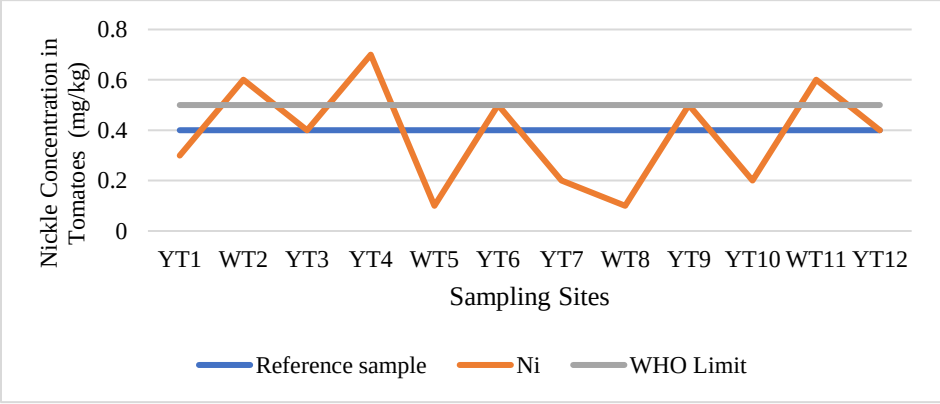
4.3.3 Lead (Pb)



(Figure No. 4.3.3 Showing the Pb Concentration in Tomato samples)

The above figure shows that lead (Pb) concentrations in several tomato samples exceeded the Reference value (0.1 mg/kg) and the WHO standards (0.3 mg/kg). Samples such as YT1 (0.4 mg/kg), WT2 (0.7 mg/kg), YT6 (0.6 mg/kg), YT7 (0.9 mg/kg), WT11 (0.6 mg/kg), and YT12 (0.9 mg/kg) exceeded the permissible limit. Sample YT4, WT5, WT8, and YT10 (all at 0.2 mg/kg) were detected below the limit. The higher Pb insamples can be associated with the source of canal water used for irrigation.

4.3.4 Nickle (Ni)



(Figure No. 4.3.4 Showing the Ni Concentration in Tomato samples)

The Nickel (Ni) concentration in tomato samples was more in line with the allowable level of 0.5 mg/kg, set by the World Health Organization. Only two samples have been slightly above the allowable limit: Sample 2 (0.6 mg/kg) and Sample 11 (0.6 mg/kg). The other samples, Sample 5 (0.1 mg/kg), Sample 7 (0.2 mg/kg), and Sample 8 (0.1 mg/kg) were within the allowable limit. Couple of samples likely had slightly higher values of Nickel (Ni) due to either contaminated sources for irrigation purposes or simply uptake from soil, potentially once rich in nickel concentration. It may cause thechronic exposures if tomatoes are consumed frequently with higher concentrations of Nickel (Ni).

4.4 Health Risk Assessment

4.4.1 Geo Accumulation Index

The Geo Accumulation index of heavy metals of the study area was calculated by using the equation $Igeo = log2\ (Cn\ /\ K.Bn\ )$

The degrees of GAI for polluted, unpolluted and extremely polluted are shown in the table given below.

Table 4.1 shows the degrees of GAI

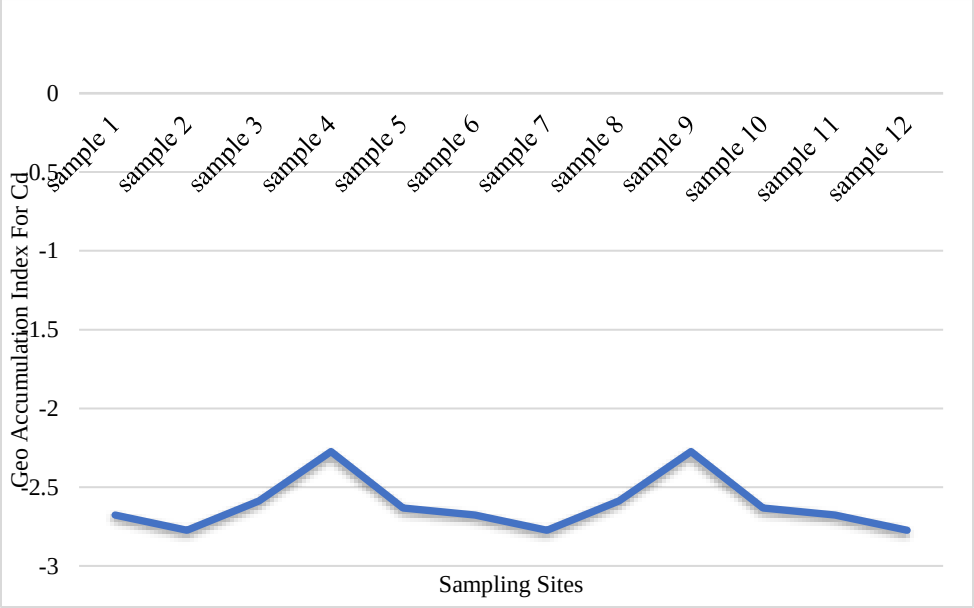
Igeo value	Degree
Igeo<0	Unpolluted
0≤Igeo<0	Unpolluted to moderate
1 ≤ Igeo<2	Moderate
2 ≤ Igeo< 3	Moderate to heavy
3 ≤ Igeo<4	Heavily
4 ≤ Igeo<5	Heavily to extremely polluted
Igeo>5	Extremely polluted

The trend of Geo-accumulation index of heavy metals based on mean log values shows that Pb > Cr > Ni > Cd, which reveals that Lead had the greatest mean concentration in the samples, while the lowest mean was indicated by Cadmium.The consistently high mean log value of Pb represents the dominant heavy metal found in the Study area.

Tabe no 4.2. Geo-accumulation index for the soil of district Swabi

Parameter	Min	Max	Mean
Cd	-2.77356	-2.27399	-2.61151
Cr	1.378834	2.046259	1.726261
Pb	8.042406	8.749209	8.348847
Ni	-0.22466	0.540877	0.247737

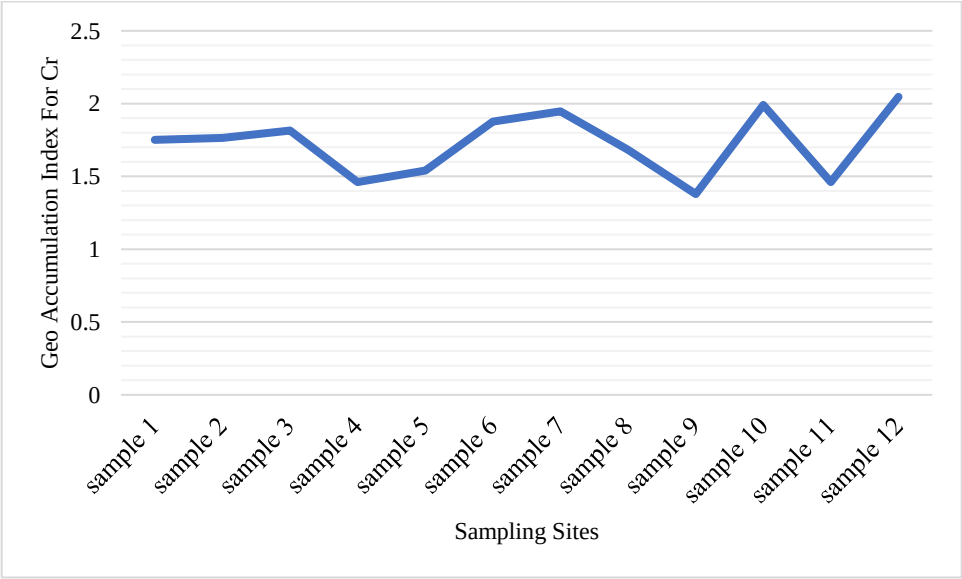
4.4.1.1 Cadmium



(Figure No. 4.4.1.1 shows Geo accumulation index for Cd)

The above figure shows the findings of the geo-accumulation index (Igeo) for Cadmium in the soil samples of the study area. The results of (Igeo) for Cadmium ranged from -2.27 to -2.77. The highest log values (-2.27) were recorded in Samples 4 and 9, indicating that this location would have slightly higher Cd accumulation compared to the other samples, but still in a low contamination class. The samples with the lowest log values (~ -2.77) were Samples 2, 7, and 12, which show slightly lower Cd concentrations. In general, when analyzing the Igeo accumulation factor, there is minimal to low Cd contamination in the area, as all values are nearing zero, or considered "uncontaminated to moderately contaminated", as classified by Igeo.

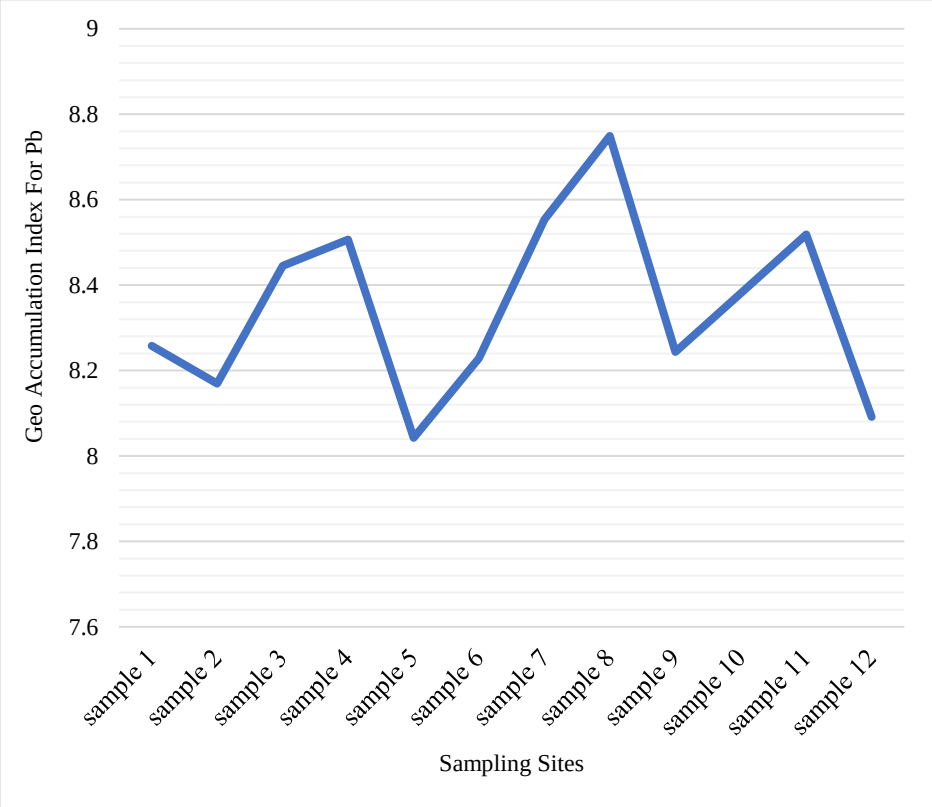
4.4.1.2 Chromium



(Figure No. 4.4.1.2 shows Geo accumulation index for Cr)

The figure illustrates the geo-accumulation index (Igeo) values for Chromium across the twelve soil samples. The log Igeo values for samples in this study range from 1.37 to log 2.04 which indicates moderate levels of Cr contamination. Sample 12 had the highest log Igeo value (log 2.04), while samples 10 (log 1.99) and 7 (log 1.94) indicated moderately elevated Cr accumulation, at least compared to the other samples. Sample 9 (log 1.379) had the lowest Igeo value, while samples 4 and 11 (both ~log 1.46) also had the relatively low Cr values, although in all three, the level of Cr enrichment was still significant. Since Igeo values in this study, which fell in the range from 1 to 2, are considered “moderately contaminated" and values over 2 indicate the transition to "moderately to heavily contaminated", the findings from Igeo indicate the presence of moderate, but variable amounts of Chromium across the study area.

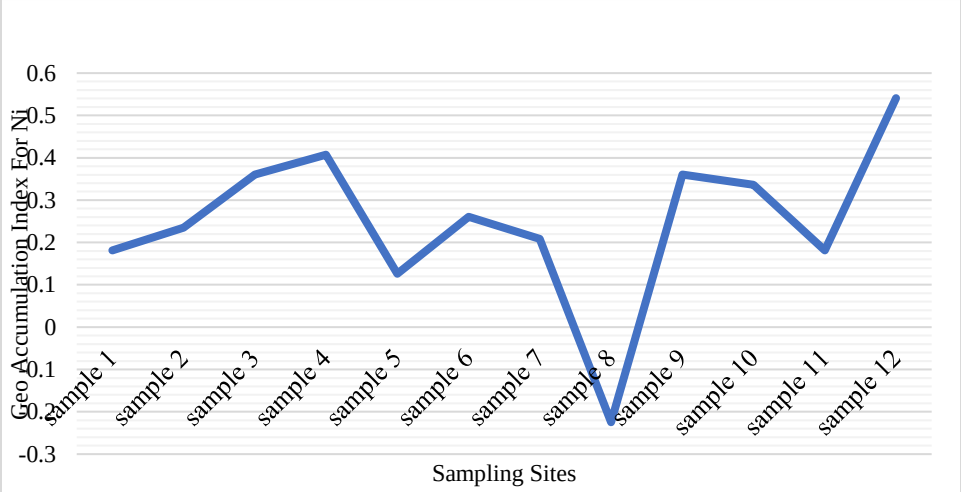
4.4.1.3 Lead



(Figure No. 4.4.1.3 shows Geo accumulation index for Pb)

The figure presents the Geo-accumulation Index (Igeo) values for Lead (Pb) found across soil samples. The log values ranged from 8.04 to 8.75, with Sample 8 containing the highest value (8.75), which indicates the most accumulation of lead in that area. This was followed by Sample 7 (8.55) and Sample 11 (8.52) which also had elevated Pb contamination. On the other hand, Sample 5 (8.04) and Sample 12 (8.09) displayed the lowest Igeo values of the samples, but those are still substantial amounts of Pb. Overall, it would appear that all sampling sites obtained a considerable amount of lead accumulation, which may potentially put them into the “heavily to extremely contaminated” category.

4.4.1.4 Nickle

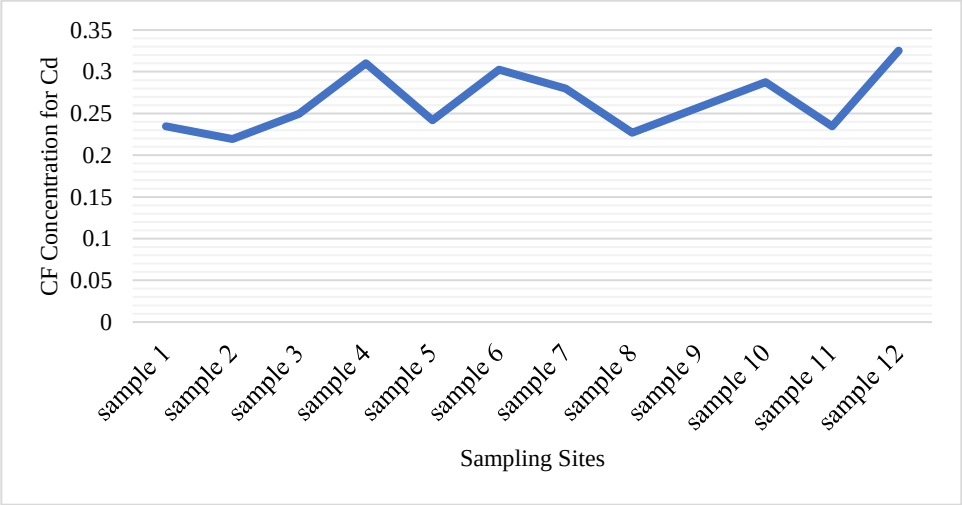


(Figure No. 4.4.1.4 shows Geo accumulation index for Ni)

The figure shows the Geo-accumulation Index (Igeo) for Nickel in the soil samples. The values range from -0.22 to 0.54, showing a lower to moderate level of contamination than, such as Pb. Sample 12 shows the highest Igeo value for Ni (0.54), indicating a moderate level of accumulation of Nickel, trailed by sample 4 (0.41), sample 3 and 9 (0.36), and sample 10 (0.34) for Ni elements. These values suggest a minimal anthropogenic or possibly local source of Ni (Nickel) contamination. However, Sample 8 has a negative log Igeo (-0.22), which indicates "uncontaminated". The other samples with Igeo close to zero values (for example, Sample 5 and Sample 1) had fewer levels of Nickel, possibly with little pollution.

4.4.2 Contamination Factor

4.4.2.1 Cadmium

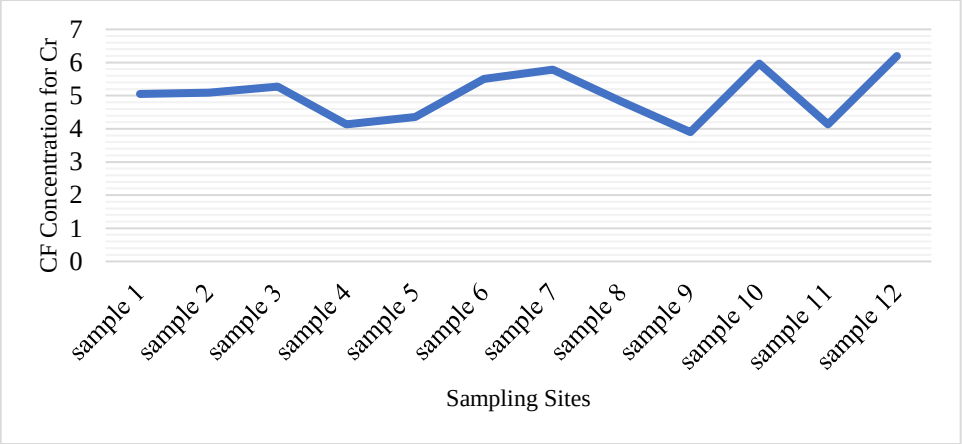


(Figure No. 4.4.2.1 Showing C.F Concentration for Cd)

The contamination factor (CF) of cadmium (Cd) for all samples was found to be less than 1, indicating low contamination. The figure indicates the CF values for Cd that were between 0.219 (Sample 2) and 0.325 (Sample 12). The largest CF value was found for Sample 12 (0.325) and was followed by Sample 4 (0.310) and Sample 6 (0.303). This indicates that cadmium

contamination is not immediate in the soils sampled, and due to the low CF values and uniformity across samples observed in the Figure, it is likely due to uniform environmental conditions and less than expected contamination from household and industry in the area.

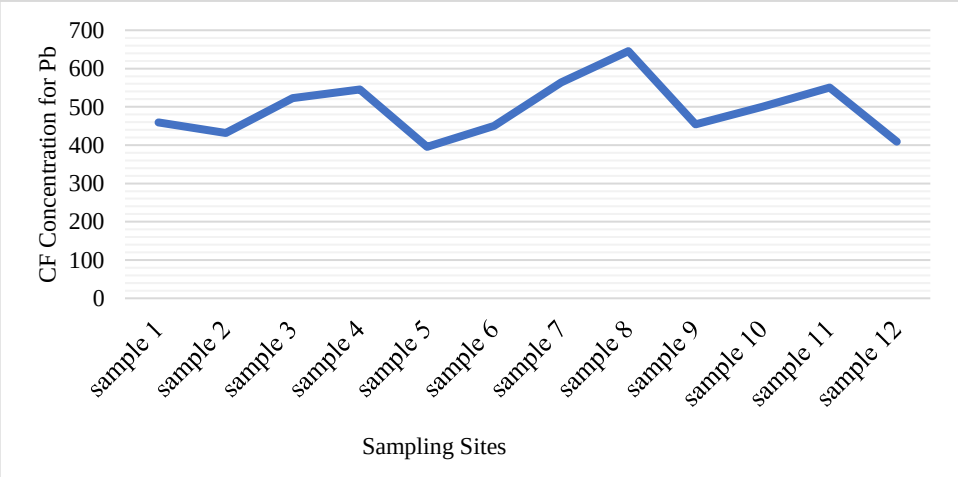
4.4.2.2 Chromium



(Figure No. 4.4.2.2 Showing C.F Concentration for Cr)

The reported contamination factor (CF) values for chromium (Cr) in the study site ranged from 3.90 to 6.20, indicating a considerable to very high level of contamination. The samples with CF values between 3 and 6 indicate a considerable level of contamination, whereas a CF greater than 6 indicates a very high level of contamination. The highest CF value (6.20) was Sample 12, which was most likely classified into the very high category (Figure-4.4.2.2). Sample 10 (5.97), Sample 7 (5.78), and Sample 6 (5.51) were the next highest CF values that were classified as considerably contaminated. The lowest CF was Sample 9 (3.90), which was still appreciably enriched above 3 and considered considerably contaminated. Given these results, it is reasonable to infer that there was a significant input of chromium from anthropogenic sources such as industrial effluents, irrigation practices from wastewater.

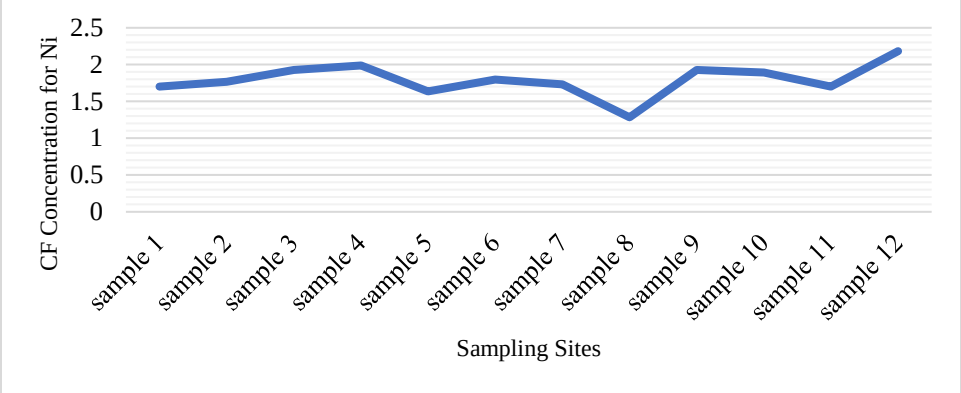
4.4.2.3 Lead



(Figure No. 4.4.2.3 Showing CF Concentration for Pb)

The contamination factor (CF) for Pb was calculated in the range of 395.45 to 645.45, suggesting very high contamination for all sites sampled (Figure-4.4.2.3). In this case, the CF values were obtained for all samples exceeding that threshold and indicating extreme enrichment of Pb in the soil. The highest CF was calculated for Sample 8 (645.45), the lowest CF value was observed for Sample 5 (395.45).

4.4.2.4 Nickle

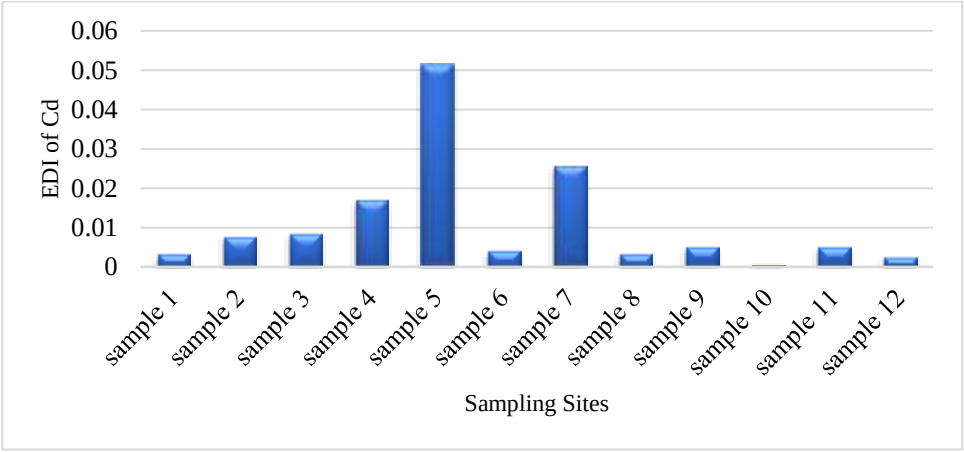


(Figure No. 4.4.2.4 Showing Contamination factor for Ni)

Nickel (Ni) contamination factor (CF) values were moderate, from 1.28 (Sample 8) to 2.18 (Sample 12). Nickel is present in elevated levels due to anthropogenic activities and these CF values indicated no concern for significant or severe levels of Ni. The contaminant factor (CF) value for Sample 12 was highest for Nickel at 2.18, followed by Sample 4 (1.98), Sample 3 and 9 (1.93), and Sample 10 (1.89) (FigureNo.4.4.2.4). While the lowest values were calculated for Sample 8 with a CF value of 1.28. The CF values were relatively uniform and moderate, indicating a greater extent of nickel enrichment from a variety of sources, most likely agricultural runoff, industrial effluents, or possible canal water used for irrigation. None of the samples show alarming levels of nickel contamination but chronic exposure to moderate levels of Ni may lead to soil degradation and crop toxicity, showing synergistic effects especially in combination with other metal contaminations.

4.4.3 Estimated Daily Intake

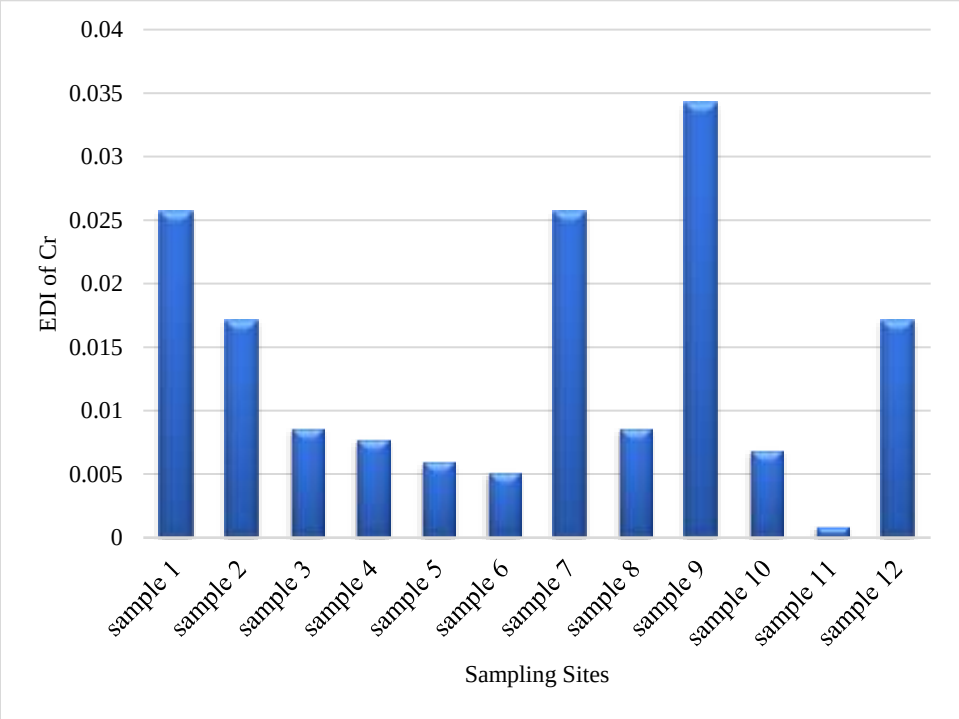
4.4.3.1 Cadmium



(Figure No. 4.4.3.1 shows the EDI of Cd)

The Estimated Daily Intake (EDI) of Cadmium (Cd) from tomato samples was assessed against the WHO safe limit of 0.001 mg/kg/day. Results revealed that 11 out of 12 samples exceeded the permissible limit, highlighting a potential health risk. The highest EDI was observed in Sample 5 (0.0514 mg/kg/day), which is more than 50 times above the recommended value. Even the lowest values among the exceeding samples, such as Sample 1 and Sample 8 (0.0034 mg/kg/day), were still more than three times higher than the safe threshold. Only Sample 10 (0.00086 mg/kg/day) fell within the permissible range, suggesting relatively lower risk. Overall, the elevated Cd intake across most samples underscores a serious public health concern, particularly in communities consuming tomatoes irrigated with contaminated canal water.

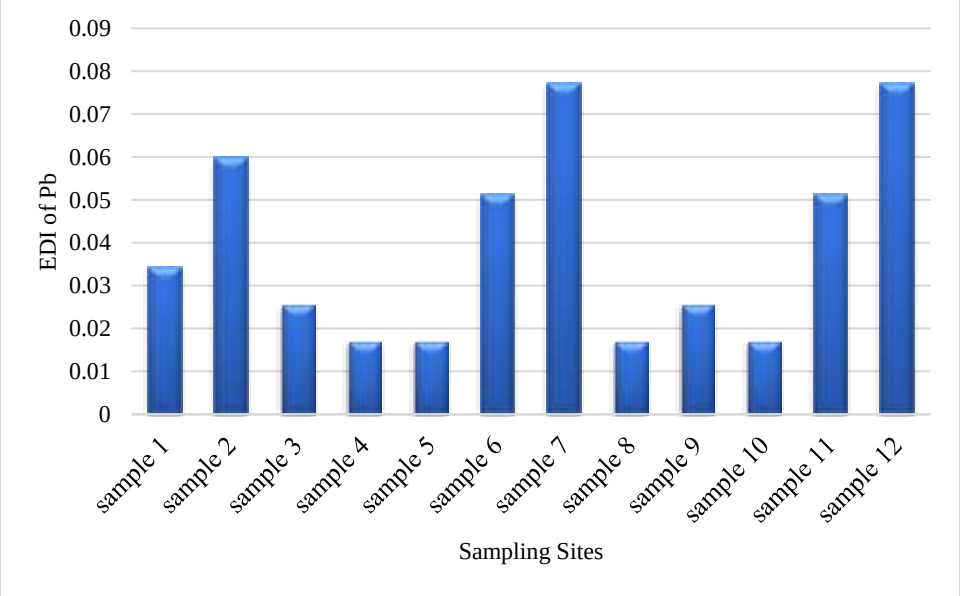
4.4.3.2 Chromium



(Figure No. 4.4.3.2 shows the EDI of Cr)

The figure indicates the Estimated Daily Intake of Chromium (Cr) for vegetable samples. The safe daily intake of Cr is recommended to be 0.003 mg/kg/day by the World Health Organization. For the EDI results, the estimate shows that 92% of the samples exceeded the WHO Standards of Cr, which poses a significant risk for public health. The maximum estimate EDI value was shown by YS9 (i.e.0.0343 mg/kg/day) which is approximately >11 times greater than the WHO Standards. YT1 and YT7 at 0.0257 mg/kg/day also were shown to have a very high estimated EDI, as well, and YT11 (0.00086 mg/kg/day) only barely remained below the safe limit. In addition to only having Sample 11 estimate Cr below the threshold of concern, the estimates for Cr across all samples range from 0.0051 to 0.0257 mg/kg/day, a significant range above an acceptable level.

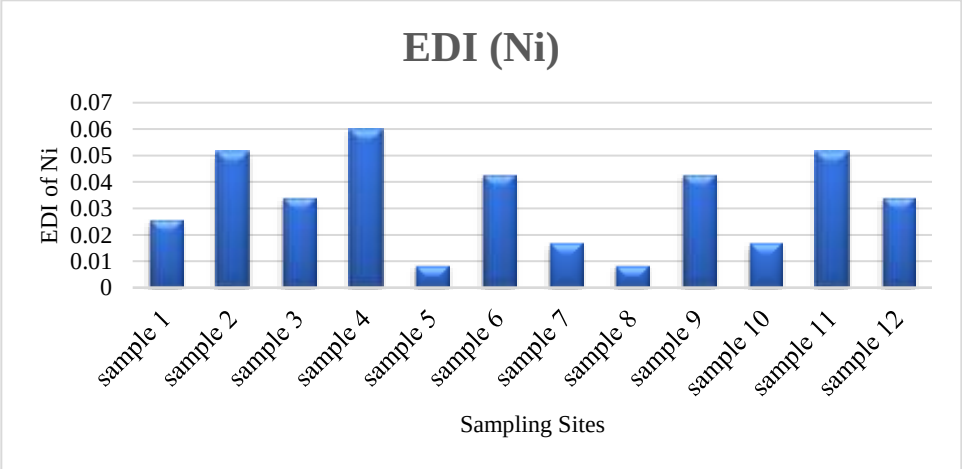
4.4.3.3 Lead



(Figure No. 4.4.3.3 shows the EDI of Pb)

The graph indicates the (EDI) of Lead (Pb) for vegetable samples. The WHO recommends a maximum safe limit of 0.0036mg/kg/day of lead intake. In consideration of the findings, it is a serious public health concern to have all 12 samples exceed the WHO Standards. The highest EDI of samples 7 and 12 (0.0771 mg/kg/day), which was more than 21 times the recommendation. Some of the other high values included Sample 2 (0.06 mg/kg/day), Sample 6 and Sample 11 (0.0514 mg/kg/day) and Sample 1 (0.0343 mg/kg/day). Samples 4, 5, 8 and 10 were the lowest (0.0171 mg/kg/day), which are still almost 5 times above the WHO guidelines.

4.4.3.4 Nickle



(Figure No. 4.4.3.4 shows the EDI of Ni)

The figure indicates that amounts of nickel (Ni) in most vegetable samples exceed the WHO recommended limit of 0.02 mg/kg/day for the daily intake of Ni. Out of the twelve samples, nine had an estimated daily intake value greater than the maximum. The largest estimated amount was in sample 4 (0.06 mg/kg/day), followed by sample 2 and sample 11 (0.0514 mg/kg/day). The

remaining samples (5, 8 and 10) were within the recommended range. These findings suggest possible considerable contamination, likely because of irrigation with untreated canal water or because of existing Ni contamination of the soil.

4.5 Discussion

The study found that elevated levels of Cd (up to 0.58 mg/kg), Cr (0.29 mg/kg), Pb (0.95 mg/kg), and Ni (0.66 mg/kg) were higher than the prescribed limits that exceeded international limits of safety. (Khan et al.,2022) identified the primary cause of contamination from the modelling as being mainly attributed to the irrigation using industrial and domestic wastewater, which is similar to the area in this study. The similarities in findings act to strengthen our conclusions that the use of wastewater for agriculture can significantly increase the risk of toxic metal uptake in vegetables. Their health risk assessment also determined that the Estimated Daily Intakes (EDIs) values for both children and adults were above the safety levels, particularly for lead and cadmium.

Our study showed significantly elevated cadmium (Cd), chromium (Cr), lead (Pb) and nickel (Ni) concentrations in the soil of irrigation sites using contaminated canal water in Swabi, with Cd 1.3, Cr 2.0, Pb 2.9, and Ni 2.1, all levels higher than their respective allowable limits from FAO/WHO. We have documented extreme contamination status of the soil, likely as result of extended use of untreated wastewater and canal water, which arrives at the farms from household and industrial effluents.

Consistent with (Hamoud et al.,2024) studied other sources of soils irrigated with wastewater in Faisalabad Pakistan. They reported Cd levels of 0.06-1.25 mg/kg, Pb levels of 0.92-2.4 mg/kg, and beyond the maximum allowable limits for Ni and Cr. Overall, these findings imply that wastewater irrigation methods represent a potentially ubiquitous source of heavy metal accumulation in agricultural soils over diversified regions of Pakistan, principally in large areas characterized by unregulated agricultural practices. This comparison indicates that direct industrial effluent disposal, especially tanneries and metal workshops, will probably be contaminating the nearby canal systems that are widely used for irrigation practices without treatment. (Aftab et al.,2023) found heavy metals in assisted irrigation systems to be significantly lower where in the soil cadmium levels had concentrations below 0.1 mg/kg and lead below 0.5 mg/kg. The divergence in this finding from our own observations could likely be attributed to the waste water treatment processes functionality in that site reducing metal concentrations. (Ahmad et al.,2022) also analyzed agricultural soil in Peshawar and found levels of Pb (to 2.1 mg/kg) and Ni (to 1.8 mg/kg) which were notable after putative irrigation with mixed sewage with canal water. The authors suggested that Poor and inadequate waste management and monitoring are contributors to their contamination levels, reasserting the regime pattern we observed in our research area.

The results of our metals research are also very similar to the findings of Vehari District, Pakistan when compared to previous outlined comparisons. (Sarwar et al.,2020) also found that total concentrations of Cd, Cu, Ni, Pb, and Cr were above thresholds, that means toxic concentrations, when soils are irrigated using direct application of raw textile and city wastewater. As for our study, (Sarwar et al.2,020) identified toxic values of Cd and Cr, total concentrations which were well above the WHO thresholds, indicating similar trends from other studies. This emphasizes the need to have government regulation of wastewater in Punjab.

Another study for comparison was research by Shafiq et al. (2017) who studied soils and vegetables irrigated with sewage and groundwater in the Rawalpindi Taxila region (northern Pakistan). They found significant levels of Cd (1.1–2.5 mg/kg), Pb, Cr, and Ni in soils and tissues of plants grown with sewage irrigation, which corroborated our findings, especially for Cd (up to 1.3 mg/kg) and Pb (up to 2.9 mg/kg) and supports the overarching conclusion that heavy metals are added to agricultural soils due to sewage and industrial effluents used for irrigation.

The soil samples from Swabi demonstrated multiple heavy metals exceeding permissible level standards: cadmium (Cd) contamination of

1.3 mg/kg; chromium (Cr) contamination of 2.0 mg/kg; lead (Pb) contamination levels were 2.9 mg/kg; and nickel (Ni) contamination of 2.1 mg/kg. The findings of this study support the findings of (Atta et al.,2022) in Dera Ghazi-|Khan, showing significant contamination and at a high level for chromium (Cr) and lead (Pb) as primary contaminates. The soil our samples were collected from had all all-shown contamination at significant levels (Cr) and Pb and Ni concentrations higher than acceptable rainfall safe limits. The concurrent concentrations illustrate that long-term irrigation of the area with contaminated canal or sewage water could leave a footprint of contamination another place in Punjab. Furthermore, the influence is not only limited or restricted to coastal industrial area.

Our soil samples from Swabi contained significant amounts of Cd (1.3 mg/kg), Cr (2.0 mg/kg), Pb (2.9 mg/kg), and Ni (2.1 mg/kg) and these heavy metals are above which FAO/WHO considered safe limits. Haroon et al. (2019) found similar contamination patterns in Abbottabad, Pakistan; whereby utilising industrial wastewater during long-term irrigation resulted in increased concentrations of Cd (~1.4 mg/kg), Cr (~1.8 mg/kg), and Pb (~2.2 mg/kg) found in the soil which were also above safe limits. The comparison of heavy metals from this study and the study conducted by (Haroon et al.,2019) shows that even when rural areas received irrigation through untreated wastewater, through around or toward industrial area, indicative of an area where industrial wastewater irrigation occurred for a long time had impeccable level of heavy metals contaminating soils in Khyber Pakhtunkhwa.

The findings of our study are consistent with (Kalsom et al.,2023) study in Faisalabad, which reported a noticeable accumulation of heavy metals in the soil with untreated urban wastewater irrigation. More specifically, they reported data of Cd (~1.1 mg/kg), Cr (~1.5 mg/kg), Pb (~2.0 mg/kg) and Ni (~2.3 mg/kg), similar to elevated levels of metals in Swabi. Collectively, these studies demonstrate a relationship between untreated municipal-industrial wastewater irrigation and accumulation of heavy metals in soil, and clearly establish the need for adequate monitoring and improved treatment of wastewater.

In the canal water samples, concentrations of cadmium (Cd), chromium (Cr), lead (Pb), and nickel (Ni) were all above permissible limits (Cd 0.1 mg/L, Cr 1 mg/L, Pb 0.5 mg/L, Ni 1 mg/L), with maximum concentrations of 0.174 mg/L, 1.378 mg/L, 3.83 mg/L, and 3.887 mg/L, respectively. These concentrations of drinking water were very similar to those reported by (Kaur et al.,2022) which detected higher concentrations of Cd, Cr, Pb, and Ni, in irrigation canals associated with industrial operations, and whose findings attributed increased contaminant values considerably to industrial discharges, residential sewer effluents, and ineffective or absent wastewater treatment (Kaur et al., 2025). The specific similarity of our values with (Kaur et al.,2025) is an indication that industrial effluents and urban sewage has caused heavy metal pollution in irrigation water in agricultural channels in Punjab. However, the findings of (Afzaal et al.,2022), who reported metals were below safety concentrations (treated canal water in southern Punjab and ~ Cr 0.75 mg/L, Ni ~0.9 mg/L, Pb <0.5 mg/L) are at odds with our values. The discrepancy in reported values, which may likely reflect the improvement in treatment practices, and limiting discharge of the effluent to regulated limits in the study area of (Afzaal et al.,2022), versus the direct and untreated application of unregulated wastewater entering into the irrigation/drainage network in our study area.

The concentrations of Cd, Cr, Pb, and Ni in our canal water samples were all above the permissible limits (Cd: 0.1 mg/L, Cr: 1 mg/L, Pb: 0.5 mg/L, Ni: 1 mg/L), which were consistent with (Saleem et al.2,019) who indicated a one-dimensional contamination profile in the River Kabul system (Ni > Pb > Cr > Cd) with concentrations for Ni (1.204 mg/L), Pb (0.479 mg/L), Cr (0.290 mg/L), and Cd (0.476 mg/L) being above the allowed limits. The order of metals and their values in our dataset, with Ni (up to 3.887 mg/L), Pb (up to 3.83 mg/L), Cr (up to 1.378 mg/L) and Cd (up to 0.174 mg/L) are consistent with a much larger scale of a national problem of contamination of

Pakistan's irrigation sources by industrial and urban wastewaters. As (Atta et al.,2023) measured the Pb, Cd and Ni levels in parts of southern Punjab (Bahawalpur, Rahim Yar Khan) and detected levels lower than permissible limits. The difference in the findings may be due to non-high industrial activities, a low population, low vehicular movement and thus minimal anthropogenic heavy metals entering into the water systems. In addition, some areas irrigate primarily from groundwater or tube wells, which are often less prone to surface runoff or contamination than open canal systems. Conversely, our study area channels continuous outflows from domestic drains, agricultural runoff, and ad-hoc refuse disposal which most likely caused the high concentrations of some heavy metals such as Pb and Ni.

The outcomes of the present study showed that the concentrations of heavy metals cadmium (Cd), chromium (Cr), lead (Pb), and nickel (Ni) for multiple tomato samples were above the permissible limits recommended by WHO/FAO particularly samples WT5, YT4, and YT7 as well as demonstrated in this study consistency with the study of (Atta et al.,2023), who evaluated heavy metal accumulation in vegetables, including tomatoes, irrigated with untreated waste water in Dera Ghazi Khan (Pakistan). (Atta et al.,2023) reported heavy metal values higher than those of WHO/FAO safety limits as well as reported that tomatoes obtained Cd (up to 0.65 mg/kg), Cr (up 0.39 mg/kg), Pb (0.89 mg/kg), and Ni (0.83 mg/kg) were above WHO/FAO safety limits.

The findings of the present study show that large numbers of tomato samples were above the WHO/FAO acceptable limits for cadmium (0.05 mg/kg), chromium (0.1 mg/kg), and lead (0.3 mg/kg), especially tomato samples of WT5, YT4, and YT7. This finding aligned with the study of Khan et al. (2022), who found high levels of metal accumulation in tomatoes grown with wastewater in Khyber Pakhtunkhwa region of Pakistan. The study found elevated levels of Cd (up to 0.58 mg/kg), Cr (0.29 mg/kg) Pb (0.95 mg/kg), and Ni (0.66 mg/kg) were higher than the prescribed limits that exceeded international limits of safety.

(Khan et al.,2022) identified the primary cause of contamination from the modelling as being mainly attributed to the irrigation using industrial and domestic wastewater, which is similar to the area in this study. The similarities in results act to strengthen our conclusions that the use of wastewater for agriculture can significantly increase the risk of toxic metal uptake in vegetables. Their health risk assessment also determined that the Estimated Daily Intakes (EDIs) and Target Hazard Quotient (THQ) values for both children and adults were above the safety levels, particularly for lead and cadmium.

Elevated levels of cadmium (up to 0.6 mg/kg), chromium (up to 0.4 mg/kg), lead (up to 0.9 mg/kg) and nickel (max 0.6 mg/kg) were found in the tomato samples in this study, which were compared to levels reported by (Nawab et al.,2018) who examined vegetables including tomatoes which received irrigation by sewage and industrial wastewater in Pakistan. They similarly found significant contamination from these metals with Cr, Ni, Pb, and Cd far greater than WHO/FAO limits of 0.1 mg/kg for Cr and Cr (0.84 mg/kg), Cd (0.186 mg/kg), Pb (0.84 mg/kg) and Ni (9.24 mg/kg) for vegetables, with similar patterns of heavy metal accumulation in edible crops. HRI of their study, tomato was listed as food items with higher risk (HRI ≈ 4.7) and chromium (HRI ≈ 2.95) was ranked most impactful on non-carcinogenic risk level.

The high levels of heavy metals in our tomato samples, especially, cadmium (Cd max 0.6 mg/kg), chromium (Cr max 0.4 mg/kg), lead (Pb max 0.9 mg/kg) and nickel (Ni max 0.6 mg/kg), are closely connected with (Tabassam et al.,2021) who investigated metal accumulation in tomato fruits irrigated with untreated wastewater in Faisalabad, Pakistan. (Tabassam et al.,2021) reported very high levels of Pb (~30–35 mg/kg in mesocarp) and substantial increases in Ni, with these concentrations was much higher than the permissible limit set by WHO/FAO. While they reported lower levels of Cd and Cr in fruit tissues, their contamination pattern is closely matched with the work we conducted, especially with Pb and Ni in relation to the pattern shown in our samples.

5. Conclusion and Recommendations

5.1 Conclusion

The outcomes of the current study showed that the levels of heavy metals like, cadmium, chromium, lead, and nickel for multiple tomato samples were exceeded the WHO standards particularly samples WT5, YT4, and YT7 as well as demonstrated in this study consistency with the study of (Atta et al.,2023), they evaluated heavy metal accumulation in vegetables, including tomatoes, irrigated with untreated waste water in Dera Ghazi Khan (Pakistan).

The result of the current study indicates that tomato samples were above the WHO/FAO acceptable limits for cadmium (0.05 mg/kg), chromium (0.1 mg/kg), and lead (0.3 mg/kg), especially tomato samples of WT5, YT4, and YT7. This finding aligned with the study of Khan et al. (2022), who found high levels of metal accumulation in tomatoes grown with wastewater in the Khyber Pakhtunkhwa region of Pakistan.

Elevated levels of cadmium (up to 0.6 mg/kg), chromium (up to 0.4 mg/kg), lead (up to 0.9 mg/kg) and nickel (max 0.6 mg/kg) were found in the tomato samples in this study, which were compared to levels reported by (Nawab et al.,2018) who examined vegetables including tomatoes which received irrigation by sewage and industrial wastewater in Pakistan. They similarly found significant contamination from these metals with Cr, Ni, Pb, and Cd far greater than WHO/FAO limits of 0.1 mg/kg for Cr and Cr (0.84 mg/kg), Cd (0.186 mg/kg), Pb (0.84 mg/kg) and Ni (9.24 mg/kg) for vegetables, with similar patterns of accumulation of heavy metal in edible crops. HRI of their study, tomato was listed as a food item with a higher risk (HRI ≈ 4.7) and chromium (HRI ≈ 2.95) was ranked most impactful on the non-carcinogenic risk level.

The higher levels of heavy metals in our tomato samples, especially, cadmium (Cd max 0.6 mg/kg), chromium (Cr max 0.4 mg/kg), lead (Pb max 0.9 mg/kg) and nickel (Ni max 0.6 mg/kg), are closely connected with (Tabassam et al.,2021) who investigated metal accumulation in tomato fruits irrigated with untreated wastewater in Faisalabad, Pakistan. (Tabassam et al.,2021) reported very high levels of Pb (~30–35 mg/kg in mesocarp) and substantial increases in Ni, with these concentrations were above the permissible limit WHO. While they reported lower concentrations of Cd and Cr in fruit tissues, their contamination pattern is closely matched with the work we conducted, especially with Pb and Ni in relation to the pattern shown in our samples.

5.2 Recommendations

Water Quality Monitoring

It is highly recommended that irrigation canal water be routinely tested for contaminants (e.g., heavy metals, pathogens, chemical residues). Communities can set up water testing units to provide early detection of pollution, and in areas where contamination is known, encouraging simple treatment options like sedimentation tanks, bio-filters, or low-cost filtration systems would mitigate harmful exposure of crops to contaminants and promote soil health and human safety.

Awareness and Training Programs for Farmers

Local farmers need to be educated about the harm of using polluted water, especially with regard to crops like tomatoes that are eaten raw. Governmental agricultural departments, NGOs, and other departments should engage farmers in awareness campaigns and educational sessions that would better inform them in using sustainable irrigation practices, vegetable handling post-harvest, and reduce direct contact with contaminated water. By providing farmers with an education, both farming production and food safety will be improved.

Adoption of Good Farming Practices

Farmers can be encouraged to implement Good Agricultural Practices (GAP) to enhance soil resilience, reduce pollutant uptake by plants, and improve crop health, including practices such as increasing the use of crop rotation, organic manure and proper chemical fertilizer applications. Training and support need to be made available to farmers to assist their transition from traditional to sustainable and healthful farming practices.

Policies and Regulation Enforcement

Government institutions must strictly regulate with respect to the control of industrial, agricultural, and domestic effluents being discharged into irrigation canals. This can be done through a monitoring protocol that enforces real-time reporting and periodic inspections. Some deterrents can reduce the risks of pollution if polluters can be fined and closed down while being subject to prohibition for illegal discharges. Strict government policies well enacted can improve the quality of water and allow good agriculture to sustain lifestyles.

Community Health Monitoring

Regular medical check-ups and health surveillance should be implemented for rural areas with contaminated vegetables. Health centers may be useful in monitoring early signs of exposure to harmful substances like lead or cadmium. Nutrition education campaigns should also be supported to ensure communities are sensible in washing, peeling, and/or cooking vegetables, limiting some risk.

Research, Collaboration and Data Sharing

Further localized research is needed to establish the impact of contaminated water on additional crops and additional communities. Research institutions and environmental management agencies should collaborate and exchange their data so that best practices can be developed in a scientifically supported manner. Collaborative partnerships between academia, industry, and governments will meaningfully contribute to effective interventions for sustainable agriculture and public health.

References

Abd Elnabi, M. K., Elkaliny, N. E., Elyazied, M. M., Azab, S. H., Elkhalifa, S. A., Elmasry, S., & Mahmoud, Y. A. G. (2023). Toxicity of heavy metals and recent advances in their removal: a review. *Toxics*, *11*(7), 580.

Abdelaal, K., AlKahtani, M., Attia, K., Hafez, Y., Király, L., & Künstler, A. (2021). The role of plant growth-promoting bacteria in alleviating the adverse effects of drought on plants. *Biology*, *10*(6), 520.

Abdel-Fattah, M. K., Abd-Elmabod, S. K., Aldosari, A. A., Elrys, A. S., & Mohamed, E. S. (2020). Multivariate analysis for assessing irrigation water quality: A case study of the Bahr Mouise Canal, Eastern Nile Delta. *Water*, *12*(9), 2537.

Abdullahi, n., igwe, e. c., & dandago, m. a. (2021). Heavy metals contamination through consumption of contaminated food crops. *Moroccan Journal of Agricultural Sciences*, *2*(1).

Abotalib, A. Z., Abdelhady, A. A., Heggy, E., Salem, S. G., Ismail, E., Ali, A., & Khalil, M. M. (2023). Irreversible and Large-Scale Heavy Metal Pollution Arising from Increased Damming and Untreated Water Reuse in the Nile Delta. *Earth's Future*, *11*(3), e2022EF002987.

Abubakar, A. R., & Haque, M. (2020). Preparation of medicinal plants: Basic extraction and fractionation procedures for experimental purposes. *Journal of Pharmacy and Bioallied Sciences*, *12*(1), 1-10.

Adnan, M., Xiao, B., Xiao, P., Zhao, P., & Bibi, S. (2022). Heavy metal, waste, COVID-19, and rapid industrialization in this modern era—Fit for sustainable future. *Sustainability*, *14*(8), 4746.

Aftab, K., Iqbal, S., Khan, M. R., Busquets, R., Noreen, R., Ahmad, N., ... & Ouladsmane, M. (2023). Wastewater-irrigated vegetables are a significant source of heavy metal contaminants: toxicity and health risks. *Molecules*, *28*(3), 1371.

Afzaal, M., Hameed, S., Liaqat, I., Ali Khan, A. A., abdul Manan, H., Shahid, R., & Altaf, M. (2022). Heavy metal contamination in water, sediments and fish of freshwater ecosystems in Pakistan. *Water Practice & Technology*, *17*(5), 1253-1272.

Agarwal, P., Vibhandik, R., Agrahari, R., Daverey, A., & Rani, R. (2024). Role of root exudates on the soil microbial diversity and biogeochemistry of heavy

metals. *Applied Biochemistry and Biotechnology*, *196*(5), 2673-2693.

Ahmad, K., Khan, Z. I., Nazar, S., Malik, I. S., Ashfaq, A., Munir, M., & Mahpara, S. (2022). Estimation of chromium in soil-plant-animal continuum: a case study in ruminants of Punjab, Pakistan. *Journal of Bioresource Management*, *9*(1), 8.

Ahmad, Z., & Ahmad, A. (2023). Socio-Cultural and Economic Consequences of Forced Marriages: A Case Study of District Swabi Tehsil Razzar. *CARC Research in Social Sciences*, *2*(1), 12-17.

Ahmed, D. A. E. A., Slima, D. F., Al-Yasi, H. M., Hassan, L. M., & Galal, T. M. (2023). Risk assessment of trace metals in Solanum lycopersicum L.(tomato) grown under wastewater irrigation conditions. *Environmental Science and Pollution Research*, *30*(14), 42255-42266.

Ahmed, D. A. E. A., Slima, D. F., Al-Yasi, H. M., Hassan, L. M., & Galal, T. M. (2023). Risk assessment of trace metals in Solanum lycopersicum L.(tomato) grown under wastewater irrigation conditions. *Environmental Science and Pollution Research*, *30*(14), 42255-42266.

Ahmed, J., Thakur, A., & Goyal, A. (2021). Industrial wastewater and its toxic effects.

Ahmed, M., Hasanuzzaman, M., Raza, M. A., Malik, A., & Ahmad, S. (2020). Plant nutrients for crop growth, development and stress tolerance. *Sustainable agriculture in the era of climate change*, 43-92.

Akhtar, A. B. T., Naseem, S., Yasar, A., & Naseem, Z. (2021). Persistent organic pollutants (POPs): sources, types, impacts, and their remediation. *Environmental pollution and remediation*, 213-246.

Akhtar, N., Syakir Ishak, M. I., Bhawani, S. A., & Umar, K. (2021). Various natural and anthropogenic factors responsible for water quality degradation: A review. *Water*, *13*(19), 2660.

Aksouh, M. Y., Boudieb, N., Benosmane, N., Moussaoui, Y., Michalski, R., Klyta, J., & Kończyk, J. (2024). Presence of Heavy Metals in Irrigation Water, Soils, Fruits, and Vegetables: Health Risk Assessment in Peri-Urban Boumerdes City, Algeria. *Molecules*, *29*(17), 4187.

Alam, M., Khan, A., Zaman, R., Khan, S., Khan, M. A., Ahmad, I., & Kim, K. I. (2024). Vermi-remediation impacts on growth and metals bioaccumulation in tomato irrigated with wastewater. *Chemosphere*, *362*, 142848.

Aleksandrov, A. P., Mirkov, I., Tucovic, D., Kulas, J., Zeljkovic, M., Popovic, D., & Kataranovski, M. (2021). Immunomodulation by heavy metals as a contributing factor to inflammatory diseases and autoimmune reactions: Cadmium as an example. *Immunology Letters*, *240*, 106-122.

Alengebawy, A., Abdelkhalek, S. T., Qureshi, S. R., & Wang, M. Q. (2021). Heavy metals and pesticides toxicity in agricultural soil and plants: Ecological risks and human health implications. *Toxics*, *9*(3), 42.

Aljamali, N. M., Mohammed, S. J., Ali, W. H., Hussein, K. M., & Salih, D. H. (2023). Pollution by sewage, chemical wastes and toxic materials: a review. *Quantum Journal of Engineering, Science and Technology*, *4*(3), 38-46.

Altaf, M. A., Hao, Y., He, C., Mumtaz, M. A., Shu, H., Fu, H., & Wang, Z. (2022). Physiological and biochemical responses of pepper (Capsicum annuum L.) seedlings to nickel toxicity. *Frontiers in Plant Science*, *13*, 950392.

Angon, P. B., Islam, M. S., Das, A., Anjum, N., Poudel, A., & Suchi, S. A. (2024). Sources, effects and present perspectives of heavy metals contamination: Soil, plants and human food chain. *Heliyon*, *10*(7).

Anwar, M., Akhtar, N., Khalid, S., & Qadar, S. (2021). 1. Eco-floristic study of weed flora of wheat crop under edaphic variation in tehsil Razar district Swabi, Khyber Pakhtunkhwa, Pakistan. *Pure and Applied Biology (PAB)*, *11*(1), 1-10.

Aslam, A., Naz, A., Shah, S. S. H., Rasheed, F., Naz, R., Kalsom, A., ... & Hussain, S. (2023). Heavy metals contamination in vegetables irrigated with wastewater: a case study of under sdeveloping regions of Pakistan. *Environmental Geochemistry and Health*, *45*(12), 8911-8927.

Aslam, M., Aslam, A., Sheraz, M., Ali, B., Ulhassan, Z., Najeeb, U., ... & Gill, R. A. (2021). Lead toxicity in cereals: mechanistic insight into toxicity, mode of action, and management. *Frontiers in plant science*, *11*, 587785.

Atta, M. I., Zehra, S. S., Dai, D. Q., Ali, H., Naveed, K., Ali, I., ... & Ali, I. (2023). Amassing of heavy metals in soils, vegetables and crop plants irrigated with wastewater: Health risk assessment of heavy metals in Dera Ghazi Khan, Punjab, Pakistan. *Frontiers in plant science*, *13*, 1080635.

Atta, M. I., Zehra, S. S., Dai, D. Q., Ali, H., Naveed, K., Ali, I., ... & Ali, I. (2023). Amassing of heavy metals in soils, vegetables and crop plants irrigated with wastewater: Health risk assessment of heavy metals in Dera Ghazi Khan, Punjab, Pakistan. *Frontiers in plant science*, *13*, 1080635.

Atta, M. I., Zehra, S. S., Dai, D. Q., Ali, H., Naveed, K., Ali, I., ... & Ali, I. (2023). Amassing of heavy metals in soils, vegetables and crop plants irrigated with wastewater: Health risk assessment of heavy metals in Dera Ghazi Khan, Punjab, Pakistan. *Frontiers in plant science*, *13*, 1080635.

Atta, M. I., Zehra, S. S., Dai, D. Q., Ali, H., Naveed, K., Ali, I., ... & Ali, I. (2023). Amassing of heavy metals in soils, vegetables and crop plants irrigated with wastewater: Health risk assessment of heavy metals in Dera Ghazi Khan, Punjab, Pakistan. *Frontiers in plant science*, *13*, 1080635.

Azhar, U., Ahmad, H., Shafqat, H., Babar, M., Munir, H. M. S., Sagir, M., ... & Khoo, K. S. (2022). Remediation techniques for elimination of heavy metal pollutants from soil: A review. *Environmental research*, *214*, 113918.

Bansal, H. (2023). Heavy metal toxicity: A comprehensive review of forms, exposure routes, toxicokinetics, and effects on infants. *International Journal of Medical Toxicology & Legal Medicine*, *26*(1and2), 13-24.

Bansal, H. (2023). Heavy metal toxicity: A comprehensive review of forms, exposure routes, toxicokinetics, and effects on infants. *International Journal of Medical Toxicology & Legal Medicine*, *26*(1and2), 13-24.

Barra Caracciolo, A., & Terenzi, V. (2021). Rhizosphere microbial communities and heavy metals. *Microorganisms*, *9*(7), 1462.

Barua, P., Islam, M. M., & Mitra, A. (2023). Accumulation of heavy metals in associated irrigated water, soil and production of tomato around the export processing zone of Bangladesh. *Asian Journal of Water, Environment and Pollution*, *20*(4), 61-67.

Bharti, B., Li, H., Ren, Z., Zhu, R., & Zhu, Z. (2022). Recent advances in sterilization and disinfection technology: A review. *Chemosphere*, *308*, 136404.

Bharti, R., & Sharma, R. (2022). Effect of heavy metals: An overview. *Materials Today: Proceedings*, *51*, 880-885.

Bottomley, P. J., Angle, J. S., & Weaver, R. W. (Eds.). (2020). *Methods of soil analysis, Part 2: Microbiological and biochemical properties* (Vol. 12). John Wiley & Sons.

Boyle, R. W., & Robinson, H. A. (2024). Nickel in the natural environment. In *Metal ions in biological systems* (pp. 1-29). CRC Press.

Cando-Dumancela, C., Davies, T., Hodgson, R. J., Liddicoat, C., Peddle, S. D., Watson, C. D., & Breed, M. F. (2023). A practical guide for restoration ecologists to manage microbial contamination risks before laboratory processes during microbiota restoration studies. *Restoration Ecology*, *31*(1), e13687.

Charkiewicz, A. E., & Backstrand, J. R. (2020). Lead toxicity and pollution in Poland. *International journal of environmental research and public health*, *17*(12), 4385.

Collin, M. S., Venkatraman, S. K., Vijayakumar, N., Kanimozhi, V., Arbaaz, S. M., Stacey, R. S., ... & Swamiappan, S. (2022). Bioaccumulation of lead (Pb) and its effects on human: A review. *Journal of Hazardous Materials Advances*, *7*, 100094.

Collin, M. S., Venkatraman, S. K., Vijayakumar, N., Kanimozhi, V., Arbaaz, S. M., Stacey, R. S., ... & Swamiappan, S. (2022). Bioaccumulation of lead (Pb) and its effects on human: A review. *Journal of Hazardous Materials Advances*, *7*, 100094.

Collins, J. F. (2021). Copper nutrition and biochemistry and human (patho) physiology. In *Advances in food and nutrition research* (Vol. 96, pp. 311-364). Academic Press.

Das, R., Saha, S., & Roymahapatra, G. (2023). Removal of hexavalent chromium ion (cr6+) from industrial effluents using low cost bioadsorbents: a review. Education in Chemical Science and Technology, 12, 53-60.

Dodman, D., Hayward, B., Pelling, M., Castán Broto, V., Chow, W., Chu, E., ... & Ziervogel, G. (2023). Cities, settlements and key infrastructure.

Dongre, R. S. (2021). Chromium & lead as soil pollutants: insights on toxicity profiles and their remediation. *Journal of Advanced Biotechnology and Bioengineering*, *9*, 1-16.

Dotaniya, M. L., Meena, V. D., Saha, J. K., Dotaniya, C. K., Mahmoud, A. E. D., Meena, B. L., ... & Rai, P. K. (2023). Reuse of poor-quality water for sustainable crop production in the changing scenario of climate. *Environment, Development and Sustainability*, *25*(8), 7345-7376.

Duan, M., Li, T., Liu, B., Yin, S., Zang, J., Lv, C., ... & Zhang, T. (2023). Zinc nutrition and dietary zinc supplements. *Critical Reviews in Food Science and Nutrition*, *63*(9), 1277-1292.

El Rasafi, T., Oukarroum, A., Haddioui, A., Song, H., Kwon, E. E., Bolan, N., ... & Rinklebe, J. (2022). Cadmium stress in plants: A critical review of the effects, mechanisms, and tolerance strategies. *Critical Reviews in Environmental Science and Technology*, *52*(5), 675-726.

El-Naggar, A., Ahmed, N., Mosa, A., Niazi, N. K., Yousaf, B., Sharma, A., ... & Chang, S. X. (2021). Nickel in soil and water: Sources, biogeochemistry, and remediation using biochar. *Journal of hazardous materials*, *419*, 126421.

Ferreira, G., Santander, A., Chavarría, L., Cardozo, R., Savio, F., Sobrevia, L., & Nicolson, G. L. (2022). Functional consequences of lead and mercury exposomes in the heart. *Molecular aspects of medicine*, *87*, 101048.

Fida, M., Li, P., Wang, Y., Alam, S. K., & Nsabimana, A. (2023). Water contamination and human health risks in Pakistan: a review. *Exposure and Health*, *15*(3), 619-639.

Fitriani, N., Wahyudianto, F. E., Salsabila, N. F., Mohamed, R. M. S. R., & Kurniawan, S. B. (2023). Performance of modified slow sand filter to reduce turbidity, total suspended solids, and iron in river water as water treatment in disaster areas. *Journal of Ecological Engineering*, *24*(1).

Francis, B., Aravindakumar, C. T., Brewer, P. B., & Simon, S. (2023). Plant nutrient stress adaptation: A prospect for fertilizer limited agriculture. *Environmental and Experimental Botany*, 105431.

Fu, B., Chen, L., Huang, H., Qu, P., & Wei, Z. (2021). Impacts of crop residues on soil health: A review. *Environmental Pollutants and Bioavailability*, *33*(1), 164-173.

Garg, S., Chowdhury, Z. Z., Faisal, A. N. M., Rumjit, N. P., & Thomas, P. (2022). Impact of industrial wastewater on environment and human health. *Advanced industrial wastewater Treatment and Reclamation of water: comparative Study of water pollution Index during pre-industrial, industrial Period and Prospect of wastewater Treatment for water resource conservation*, 197-209.

Genchi, G., Carocci, A., Lauria, G., Sinicropi, M. S., & Catalano, A. (2020). Nickel: Human health and environmental toxicology. *International journal of environmental research and public health*, *17*(3), 679.

Genchi, G., Carocci, A., Lauria, G., Sinicropi, M. S., & Catalano, A. (2020). Nickel: Human health and environmental toxicology. *International journal of environmental research and public health*, *17*(3), 679.

Gerhardsson, L. (2022). Diagnosis and treatment of metal poisoning general aspects. In *Handbook on the Toxicology of Metals* (pp. 663-684). Academic Press.

Ghosh, S., & Ghosh, S. (2021). Water crisis in urban and sub-urban areas: A global perspective. *Saudi J Bus Manag Stud*, *6*(8), 327-344.

Goh, S. X. L., Chong, B. H. D., & Lee, H. K. (2020). Fully automated water sampling–surfactant-enhanced membrane bag liquid-phase microextraction–ultrahigh performance liquid chromatography–mass spectrometry. *Analytical chemistry*, *92*(7), 5362-5369.

Gong, L., Qiu, D., Yao, X., & Yang, G. (2020, June). Determination of heavy metals in the plant sample pretreatment methods. In *Journal of Physics: Conference Series* (Vol. 1549, No. 2, p. 022008). IOP Publishing.

Goud, B. R., Raghavendra, M., Prasad, P. S., Hatti, V., Halli, H. M., Nayaka, G. V., ... & Rajpoot, S. K. (2022). Sustainable management and restoration of the fertility of damaged soils. *Agriculture Issues and Policies*, *113*.

Goyal, D., Yadav, A., Prasad, M., Singh, T. B., Shrivastav, P., Ali, A., ... & Mishra, S. (2020). Effect of heavy metals on plant growth: an overview. *Contaminants in agriculture: sources, impacts and management*, 79-101.

Gras, J. M. (2024). Conservation of the Peri-urban Landscape. In *Peri-urban Landscape* (pp. 185-216). River Publishers.

Gul, H. (2024). *Ecological distribution and assessment of mushroom species in the District Swabi, Khyber Pakhtunkhwa, Pakistan* (Doctoral dissertation, Quaid I Azam University Islamabad).

Guo, J., Muhammad, H., Lv, X., Wei, T., Ren, X., Jia, H., ... & Hua, L. (2020). Prospects and applications of plant growth promoting rhizobacteria to mitigate soil metal contamination: A review. *Chemosphere*, *246*, 125823.

Gupta, N., Yadav, K. K., Kumar, V., Krishnan, S., Kumar, S., Nejad, Z. D., ... & Alam, J. (2021). Evaluating heavy metals contamination in soil and vegetables in the region of North India: Levels, transfer and potential human health risk analysis. *Environmental toxicology and pharmacology*, *82*, 103563.

Haddad, M., Nassar, D., & Shtaya, M. (2023). Heavy metals accumulation in soil and uptake by barley (Hordeum vulgare) irrigated with contaminated water. *Scientific reports*, *13*(1), 4121.

Hafeez, A., Rasheed, R., Ashraf, M. A., Qureshi, F. F., Hussain, I., & Iqbal, M. (2023). Effect of heavy metals on growth, physiological and biochemical responses of plants. In *Plants and their interaction to environmental pollution* (pp. 139-159). Elsevier.

Hamoud, Y. A., Shaghaleh, H., Zia-ur-Rehman, M., Rizwan, M., Umair, M., Usman, M., ... & Alghanem, S. M. S. (2024). Cadmium and lead accumulation in important food crops due to wastewater irrigation: Pollution index and health risks assessment. *Heliyon*, *10*(3).

Haroon, B., Ping, A., Pervez, A., Faridullah, & Irshad, M. (2019). Characterization of heavy metal in soils as affected by long-term irrigation with industrial wastewater. *Journal of Water Reuse and Desalination*, *9*(1), 47-56.

Hasan, H. A., & Muhammad, M. H. (2020). A review of biological drinking water treatment technologies for contaminants removal from polluted water resources. *Journal of Water Process Engineering*, *33*, 101035.

Hassan, J., Rajib, M. M. R., Khan, M. N. E. A., Khandaker, S., Zubayer, M., Ashab, K. R., ... & Awual, M. R. (2024). Assessment of heavy metals accumulation by vegetables irrigated with different stages of textile wastewater for evaluation of food and health risk. *Journal of environmental management*, *353*, 120206.

Hee, Y. Y., Weston, K., & Suratman, S. (2022). The effect of storage conditions and washing on microplastic release from food and drink containers. *Food Packaging and Shelf Life*, *32*, 100826.

Hemathilake, D. M. K. S., & Gunathilake, D. M. C. C. (2022). Agricultural productivity and food supply to meet increased demands. In *Future foods* (pp. 539-553). Academic Press.

Hlihor, R. M., Roşca, M., Hagiu-Zaleschi, L., Simion, I. M., Daraban, G. M., & Stoleru, V. (2022). Medicinal plant growth in heavy metals contaminated soils: Responses to metal stress and induced risks to human health. *Toxics*, *10*(9), 499.

Hossini, H., Shafie, B., Niri, A. D., Nazari, M., Esfahlan, A. J., Ahmadpour, M., ... & Hoseinzadeh, E. (2022). A comprehensive review on human health effects of chromium: insights on induced toxicity. *Environmental Science and Pollution Research*, *29*(47), 70686-70705.

Hu, B., Jia, X., Hu, J., Xu, D., Xia, F., & Li, Y. (2017). Assessment of heavy metal pollution and health risks in the soil-plant-human system in the Yangtze River Delta, China. *International journal of environmental research and public health*, *14*(9), 1042.

Hu, W., Xia, M., Zhang, C., Song, B., Xia, Z., Guo, C., ... & Fang, J. (2021). Chronic cadmium exposure induces epithelial mesenchymal transition in prostate cancer cells through a TGF-β-independent, endoplasmic reticulum stress induced pathway. *Toxicology Letters*, *353*, 107-117.

Hussain, S., Nazir, K., Amjad, M., Kanwal, F., Khan, U., & Riaz, M. (2020). Role of heavy metals and anthropogenic activities in water contamination. *Scientific Inquiry and Review*, *4*(2), 31-47.

Iqbal, Z., Parveen, K., Ahmad, K., Ahmad, T., Riaz, N., Hussain, A., ... & Alhuthayli, R. S. (2024). Monitoring of Cadmium and Lead Accumulation in Soil-Forage-Animal Continuum in Pasture Land Irrigated with Ground Water in Bhalwal, Punjab, Pakistan. *Journal of Bioresource Management*, *11*(3), 20.

Ishaq, M., Sultana, N., Ikram, M., Iqbal, A., Shah, F., Hamayun, M., & Hussain, A. (2020). Occurrence of heavy metals and pesticide residues in tomato crop: a threat to public health. *Arabian Journal of Geosciences*, *13*, 1-11.

Islam, M. M., Mohana, A. A., Rahman, M. A., Rahman, M., Naidu, R., & Rahman, M. M. (2023). A comprehensive review of the

current progress of chromium removal methods from aqueous solution. *Toxics*, *11*(3), 252.

Jagaba, A. H., Lawal, I. M., Birniwa, A. H., Affam, A. C., Usman, A. K., Soja, U. B., ... & Yaro, N. S. A. (2024). Sources of water contamination by heavy metals. In *Membrane technologies for heavy metal removal from water* (pp. 3-27). CRC Press.

Jagetiya, B., & Kumar, S. (2020). Phytoremediation of lead: a review. *Lead in Plants and the Environment*, 171-202.

Jannetto, P. J., & Cowl, C. T. (2023). Elementary overview of heavy metals. *Clinical Chemistry*, *69*(4), 336-349.

Jomova, K., Makova, M., Alomar, S. Y., Alwasel, S. H., Nepovimova, E., Kuca, K., ... & Valko, M. (2022). Essential metals in health and disease. *Chemico-biological interactions*, *367*, 110173.

Kalsom, A., Kareem, A., Aslam, A., Niaz, A., Mukhtar, N., Sattar, A., ... & ul Haq, E. (2020). Influence of wastewater irrigation on soil chemical properties and buildup of heavy metals in soil. *EQA-International Journal of Environmental Quality*, *37*, 23-30.

Karimi-Maleh, H., Ayati, A., Ghanbari, S., Orooji, Y., Tanhaei, B., Karimi, F., ... & Sillanpää, M. (2021). Recent advances in removal techniques of Cr (VI) toxic ion from aqueous solution: A comprehensive review. *Journal of molecular liquids*, *329*, 115062.

Kaur, H., Kaur, H., Kaur, H., & Srivastava, S. (2023). The beneficial roles of trace and ultratrace elements in plants. *Plant Growth Regulation*, *100*(2), 219-236.

Kaur, N., Singh, J., Sharma, N. R., Natt, S. K., Mohan, A., Malik, T., & Girdhar, M. (2025). Heavy metal contamination in wastewater-irrigated vegetables: assessing food safety challenges in developing Asian countries. *Environmental Science: Processes & Impacts*.

Kaur, N., Singh, J., Sharma, N. R., Natt, S. K., Mohan, A., Malik, T., & Girdhar, M. (2025). Heavy metal contamination in wastewater-irrigated vegetables: assessing food safety challenges in developing Asian countries. *Environmental Science: Processes & Impacts*.

Keogh, J. P., & Siegers, C. P. (2023). Influences on the gastrointestinal system by essential and toxic metals. In *Toxicology of Metals, Volume I* (pp. 901-919). CRC Press.

Khalef, R. N., Hassan, A. I., & Saleh, H. M. (2022). Heavy metal's environmental impact. In *Environmental Impact and Remediation of Heavy Metals*. IntechOpen.

Khan, I., Akram, A., Fatima, S., Ahmad, B., Rehman, Z., Arshad, N., ... & Ahmad, Z. (2022). Problems of agriculture in Pakistan: an insight into their solution. *Pakistan Journal of Biotechnology*, *19*(02), 73-83.

Khan, Z. I., Mansha, A., Saleem, M. H., Tariq, F., Ahmad, K., Ahmad, T., ... & Ali, S. (2021). Trace metal accumulation in rice variety kainat irrigated with canal water. *Sustainability*, *13*(24), 13739.

Khanam, Z., Sultana, F. M., & Mushtaq, F. (2023). Environmental pollution control measures and strategies: an overview of recent developments. *Geospatial Analytics for Environmental Pollution Modeling: Analysis, Control and Management*, 385-414.

Khatun, J., Intekhab, A., & Dhak, D. (2022). Effect of uncontrolled fertilization and heavy metal toxicity associated with arsenic (As), lead (Pb) and cadmium (Cd), and possible remediation. *Toxicology*, *477*, 153274.

Knez, E., Kadac-Czapska, K., Dmochowska-Ślęzak, K., & Grembecka, M. (2022). Root vegetables—Composition, health effects, and contaminants. *International journal of environmental research and public health*, *19*(23), 15531.

Knorr, D., & Augustin, M. A. (2023). Vanishing water: rescuing the neglected Food Resource. *Food Engineering Reviews*, *15*(4), 609-624.

Krezel, A., & Maret, W. (2021). The bioinorganic chemistry of mammalian metallothioneins. *Chemical reviews*, *121*(23), 14594-14648.

Kumar, A., Kumar, A., MMS, C. P., Chaturvedi, A. K., Shabnam, A. A., Subrahmanyam, G., ... & Yadav, K. K. (2020). Lead toxicity: health hazards, influence on food chain, and sustainable remediation approaches. *International journal of environmental research and public health*, *17*(7), 2179.

Kumar, N., Kumar, A., Marwein, B. M., Verma, D. K., Jayabalan, I., Kumar, A., & Kumar, N. (2021). Agricultural activities causing water pollution and its mitigation–a review. *International Journal of Modern Agriculture*, *10*(1), 590-609.

Kumar, P., Goud, E. L., Devi, P., Dey, S. R., & Dwivedi, P. (2022). Heavy metals: transport in plants and their physiological and toxicological effects. In *Plant metal and metalloid transporters* (pp. 23-54). Singapore: Springer Nature Singapore.

León, O. L. L., & Pacheco, J. M. S. (2020). Effects of lead on reproductive health. In *Lead Chemistry*. London, UK: IntechOpen.

Lin, L., Yang, H., & Xu, X. (2022). Effects of water pollution on human health and disease heterogeneity: a review. *Frontiers in environmental science*, *10*, 880246.

Łyszczarz, S., Błońska, E., & Lasota, J. (2020). The application of the geo-accumulation index and geostatistical methods to the assessment of forest soil contamination with heavy metals in the Babia Góra National Park (Poland). *Archives of Environmental Protection*, *46*(3).

Mahmood, S., Kiliç, Z., Saeed, M. M., Rehman, H. A., Aslan, Z., Elsarag, E. I., ... & Haider, S. (2021). Environmental and hydrological consequences of agriculture activities: general review & case study.

Mahmoud, E. K., & Ghoneim, A. M. (2016). Effect of polluted water on soil and plant contamination by heavy metals in El-Mahla El-Kobra, Egypt. *Solid Earth*, *7*(2), 703-711.

Mandal, G. C., Mandal, A., & Chakraborty, A. (2022). The toxic effect of lead on human health: A review. *Human Biology and Public Health*, *3*.

Manisalidis, I., Stavropoulou, E., Stavropoulos, A., & Bezirtzoglou, E. (2020). Environmental and health impacts of air pollution: a review. *Frontiers in public health*, *8*, 14.

Manne, R., Kumaradoss, M. M. R. M., Iska, R. S. R., Devarajan, A., & Mekala, N. (2022). Water quality and risk assessment of copper content in drinking water stored in copper container. *Applied Water Science*, *12*(3), 27.

Manzoor, M. A., Xu, Y., Xu, J., Shah, I. H., Sabir, I. A., Wang, Y., ... & Zhang, C. (2024). Horticulture crop under pressure: Unraveling the impact of climate change on nutrition and fruit cracking. *Journal of Environmental Management*, *357*, 120759.

Mehri, A. (2020). Trace elements in human nutrition (II)–an update. *International journal of preventive medicine*, *11*(1), 2.

Mekonnen, T. T., & Taye, A. E. (2024). Potentially toxic metals in Northeast Ethiopian agricultural soils: implications for Solanum lycopersicum (Tomato) production and human health. *Environmental Geochemistry and Health*, *46*(10), 402.

Mishra, H. (2025). Environmental Degradation and Impacts on Agricultural Production: A Challenge to Urban Sustainability. In *Sustainable Urban Environment and Waste Management: Theory and Practice* (pp. 53-92). Singapore: Springer Nature Singapore.

Mishra, R. K. (2023). Fresh water availability and its global challenge. *British Journal of Multidisciplinary and Advanced Studies*, *4*(3), 1-78.

Mitra, S., Chakraborty, A. J., Tareq, A. M., Emran, T. B., Nainu, F., Khusro, A., ... & Simal-Gandara, J. (2022). Impact of heavy

metals on the environment and human health: Novel therapeutic insights to counter the toxicity. *Journal of King Saud University-Science*, *34*(3), 101865.

Monteiro De Oliveira, E. C., Caixeta, E. S., Santos, V. S. V., & Pereira, B. B. (2021). Arsenic exposure from groundwater: environmental contamination, human health effects, and sustainable solutions. *Journal of Toxicology and Environmental Health, Part B*, *24*(3), 119-135.

Mulenga, C., Clarke, C., & Meincken, M. (2020). Physiological and growth responses to pollutant-induced biochemical changes in plants: A review.

Nadarajan, S., & Sukumaran, S. (2021). Chemistry and toxicology behind chemical fertilizers. In *Controlled Release fertilizers for sustainable agriculture* (pp. 195-229). Academic Press.

Naranjo, V. I., Hendricks, M., & Jones, K. S. (2020). Lead toxicity in children: an unremitting public health problem. *Pediatric Neurology*, *113*, 51-55.

Naz, M., Dai, Z., Hussain, S., Tariq, M., Danish, S., Khan, I. U., ... & Du, D. (2022). The soil pH and heavy metals revealed their impact on soil microbial community. *Journal of Environmental Management*, *321*, 115770.

Naz, S., Anjum, M. A., Siddique, B., Naqvi, S. A. H., Sajid, A., Sardar, H., ... & Khan, Z. (2020). Effect of sewage water irrigation frequency on growth, yield and heavy metals accumulation of tomato and okra. *Pakistan Journal of Agricultural Research*, *33*(4), 798.

Newman, B., & Fourie, A. J. (2023). Sediment Sample Collection and Preparation for the Analysis of Plastic-Related Pollutants.

Nguyen, D. H. (2020). *Itai-Itai disease: the role of mining in the degradation of Japanese society and public health* (Doctoral dissertation, The Ohio State University).

Nkwunonwo, U. C., Odika, P. O., & Onyia, N. I. (2020). A review of the health implications of heavy metals in food chain in Nigeria. *The Scientific World Journal*, *2020*(1), 6594109.

Pande, V., Pandey, S. C., Sati, D., Bhatt, P., & Samant, M. (2022). Microbial interventions in bioremediation of heavy metal contaminants in agroecosystem. *Frontiers in microbiology*, *13*, 824084.

Panhwar, M. Y., Panhwar, S., Keerio, H. A., Khokhar, N. H., Shah, S. A., & Pathan, N. (2022). Water quality analysis of old and new Phuleli Canal for irrigation purpose in the vicinity of Hyderabad, Pakistan. *Water Practice & Technology*, *17*(2), 529-536.

Parida, L., & Patel, T. N. (2023). Systemic impact of heavy metals and their role in cancer development: a review. *Environmental Monitoring and Assessment*, *195*(6), 766.

Parveen, F., & Khan, S. J. (2023). Wastewater treatment in Pakistan: Issues, challenges and solutions. In *Water Policy in Pakistan: Issues and Options* (pp. 323-349). Cham: Springer International Publishing.

Peng, J., Chen, Y., Xia, Q., Rong, G., & Zhang, J. (2021). Ecological risk and early warning of soil compound pollutants (HMs, PAHs, PCBs and OCPs) in an industrial city, Changchun, China. *Environmental Pollution*, *272*, 116038.

Prakash, S., & Verma, A. K. (2021). Arsenic: it's toxicity and impact on human health. *International Journal of Biological Innovations, IJBI*, *3*(1), 38-47.

Qasim, M., Ali, N., & Aqeel, M. (2023). Trends and Patterns of Temporal Urban Population Growth in Pakistan. *Pakistan Social Sciences Review*, *7*(3), 551-564.

Rahman, M., Alam, M. U., Luies, S. K., Kamal, A., Ferdous, S., Lin, A., ... & Ercumen, A. (2021). Contamination of fresh produce with antibiotic-resistant bacteria and associated risks to human health: A scoping review. *International journal of*

environmental research and public health, *19*(1), 360.

Rani, M., Vikas, Kumar, R., Lathwal, M., & Kamboj, A. (2024). Effect and responses of lead toxicity in plants. In *Lead toxicity mitigation: sustainable Nexus approaches* (pp. 211-241). Cham: Springer Nature Switzerland.

Razzak, S. A., Faruque, M. O., Alsheikh, Z., Alsheikhmohamad, L., Alkuroud, D., Alfayez, A., ... & Hossain, M. M. (2022). A comprehensive review on conventional and biological-driven heavy metals removal from industrial wastewater. *Environmental Advances*, *7*, 100168.

Reader, G. T. (2022, June). Access to drinking water, food security and adequate housing: challenges for engineering, past, present and future. In Symposium on Responsible Engineering and Living (pp. 1-41). Cham: Springer International Publishing.

Rehman, A., Ma, H., Ozturk, I., & Ulucak, R. (2022). Sustainable development and pollution: The effects of CO 2 emission on population growth, food production, economic development, and energy consumption in Pakistan. *Environmental Science and Pollution Research*, 1-12.

Rizwan, M., Usman, K., & Alsafran, M. (2024). Ecological impacts and potential hazards of nickel on soil microbes, plants, and human health. *Chemosphere*, 142028.

Sajid, I., Tischbein, B., Borgemeister, C., & Flörke, M. (2022). Assessing barriers in adaptation of water management innovations under rotational canal water distribution system. *Agriculture*, *12*(7), 913.

Salem, M. A., Perez de Souza, L., Serag, A., Fernie, A. R., Farag, M. A., Ezzat, S. M., & Alseekh, S. (2020). Metabolomics in the context of plant natural products research: From sample preparation to metabolite analysis. *Metabolites*, *10*(1), 37.

Salem, S. H., Saber, M., Gadow, S., Kabary, H., & Zaghloul, A. (2024). Influence of the use of remediated soil and agricultural drainage water on the safety of tomato fruits. *Environmental Science and Pollution Research*, *31*(21), 31546-31561.

Sarwar, T., Shahid, M., Natasha, Khalid, S., Shah, A. H., Ahmad, N., ... & Bakhat, H. F. (2020). Quantification and risk assessment of heavy metal build-up in soil–plant system after irrigation with untreated city wastewater in Vehari, Pakistan. *Environmental geochemistry and health*, *42*, 4281-4297.

Saud, S., Wang, D., Fahad, S., Javed, T., Jaremko, M., Abdelsalam, N. R., & Ghareeb, R. Y. (2022). The impact of chromium ion stress on plant growth, developmental physiology, and molecular regulation. *Frontiers in Plant Science*, *13*, 994785.

Shafiq, M., Shaukat, T., Nazir, A., & Bareen, F. E. (2017). Modeling of Cr contamination in the agricultural lands of three villages near the leather industry in Kasur, Pakistan, using statistical and GIS techniques. *Environmental Monitoring and Assessment*, *189*, 1-18.

Shah, I. A., Khan, H., Gul, B., & Uslu, Ö. S. (2022). farmers'perception of climate change and parthenium weed distribution in district swabi, khyber pakhtunkhw. *Pakistan Journal of Weed Science Research*, *28*(3).

Shahzad, N., & Amjad, M. (2022). Climate change and food security in Pakistan. In *Sustainable agriculture and food security* (pp. 579-594). Cham: Springer International Publishing.

Sharma, U. C., Datta, M., & Sharma, V. (2023). Land use and management. In Soils in the Hindu Kush Himalayas: Management for Agricultural Land Use (pp. 295-462). Cham: Springer International Publishing.

Shelar, M., Gawade, V., & Bhujbal, S. (2021). A review on heavy metal contamination in

herbals. *Journal of Pharmaceutical Research International*, *33*(29A), 7-16.

Sherazi, T. Z., Raza, I., & Muhammad, R. (2024). Industrial Development under China Pakistan Economic Corridor (CPEC): Accomplished Lessons from China. *Journal of Professional Research in Social Sciences*, *11*(1), 24-56.

Siddiqui, S. F. (2023). study of water for pharmaceutical and biopharmaceutical purpose.

Singh, A. (2021). A review of wastewater irrigation: Environmental implications. *Resources, Conservation and Recycling*, *168*, 105454.

Singh, A. (2021). A review of wastewater irrigation: Environmental implications. *Resources, Conservation and Recycling*, *168*, 105454.

Singh, A., Sharma, A., Verma, R. K., Chopade, R. L., Pandit, P. P., Nagar, V., ... & Sankhla, M. S. (2022). Heavy metal contamination of water and their toxic effect on living organisms. In *The toxicity of environmental pollutants*. IntechOpen.

Singh, I. (2022). Impacts of heavy metals on aquatic life, soil, plants, and Human health. *Thanuj International Publishers, Tamil Nadu, India*, 43.

Singh, T. B., Ali, A., Prasad, M., Yadav, A., Shrivastav, P., Goyal, D., & Dantu, P. K. (2020). Role of organic fertilizers in improving soil fertility. *Contaminants in agriculture: sources, impacts and management*, 61-77.

Solanki, D. K., & Naval, R. K. (2023). *Introduction To Environmental Science*. ag publishing house (agph books).

Solgi, E., Sheikhzadeh, H., & Solgi, M. (2018). Role of irrigation water, inorganic and organic fertilizers in soil and crop contamination by potentially hazardous elements in intensive farming systems: Case study from Moghan agro-industry, Iran. *Journal of Geochemical Exploration*, *185*, 74-80.

STATISTICS, P. B. O. (2021). GOVERNMENT OF PAKISTAN PAKISTAN BUREAU OF STATISTICS KARACHI. *Change*, *2022*.

Suhani, I., Sahab, S., Srivastava, V., & Singh, R. P. (2021). Impact of cadmium pollution on food safety and human health. *Current opinion in toxicology*, *27*, 1-7.

Suja, S. K., Almaas, S., Gracy, A. P., Gowsika, P., Jeyapradeepa, K., Sri, G. S., ... & Asha, K. B. (2024). Contamination of Water by Heavy Metals and Treatment Methods–A Review. *Current World Environment*, *19*(1), 4.

Sultan, M., & Ahmad, F. (Eds.). (2023). Irrigation and Drainage: Recent Advances.

Susanto, A. B., Santosa, G. W., Djunaedi, A., Pringgenies, D., & Ariyanto, D. (2023). The impact of mixed feed of seaweed Gracilaria sp. and transfer factor formula on the immune response of Nile tilapia (Oreochromis niloticus). *Aquaculture, Aquarium, Conservation & Legislation*, *16*(1), 242-251.

Sut-Lohmann, M., Ramezany, S., Kästner, F., Raab, T., Heinrich, M., & Grimm, M. (2022). Using modified Tessier sequential extraction to specify potentially toxic metals at a former sewage farm. *Journal of Environmental Management*, *304*, 114229.

Tabassam, Q., Ahmad, M. S. A., Alvi, A. K., Awais, M., Kaushik, P., & El-Sheikh, M. A. (2023). Accumulation of different metals in Tomato (Lycopersicon esculentum L.) Fruits Irrigated with Wastewater. *Applied Sciences*, *13*(17), 9711.

Tambo, E., Djuikoue, I. C., Tazemda, G. K., Fotsing, M. F., & Zhou, X. N. (2021). Early-stage risk communication and community engagement (RCCE) strategies and measures against the coronavirus disease 2019 (COVID-19) pandemic crisis. *Global Health Journal*, *5*(1), 44-50.

Tariq, A., & Mushtaq, A. (2023). Untreated wastewater reasons and causes: a review of most affected areas and cities. *Int. J. Chem. Biochem. Sci*, *23*(1), 121-143.

Taux, K., Kraus, T., & Kaifie, A. (2022). Mercury exposure and its health effects in workers in the Artisanal and Small-Scale Gold Mining (ASGM) sector—A systematic review. *International journal of environmental research and public health*, *19*(4), 2081.

Taylor, A. A., Tsuji, J. S., Garry, M. R., McArdle, M. E., Goodfellow, W. L., Adams, W. J., & Menzie, C. A. (2020). Critical review of exposure and effects: implications for setting regulatory health criteria for ingested copper. *Environmental management*, *65*, 131-159.

Teixeira, F. J., & Gomes, C. S. (2021). Mineral water: Essential to life, health, and wellness. In *Minerals latu sensu and Human Health: Benefits, Toxicity and Pathologies* (pp. 517-556). Cham: Springer International Publishing.

Tóth, G., Hermann, T., Da Silva, M. R., & Montanarella, L. J. E. I. (2016). Heavy metals in agricultural soils of the European Union with implications for food safety. *Environment international*, *88*, 299-309.

Tripathi, N. (2024). ANALYSIS OF PHYSICO-CHEMICAL PARAMETERS OF RIVER GARRA AT SHAHJAHANPUR (UP). *Knowledgeable Research A Multidisciplinary Journal*, *2*(10), 55-67.

Vanisree, C. R., Sankhla, M. S., Singh, P., Jadhav, E. B., Verma, R. K., Awasthi, K. K., ... & Nagar, V. (2022). Heavy metal contamination of food crops: Transportation via food chain, human consumption, toxicity and management strategies. In *Environmental Impact and Remediation of Heavy Metals*. IntechOpen.

Varma, S., & Jangra, M. (2021). Heavy metals stress and defense strategies in plants: An overview. *Journal of Pharmacognosy and Phytochemistry*, *10*(1), 608-614.

Vasilachi, I. C., Stoleru, V., & Gavrilescu, M. (2023). Analysis of heavy metal impacts on cereal crop growth and development in contaminated soils. *Agriculture*, *13*(10), 1983.

Vincent, J. B. (2023). Chromium: Sources, Speciation, Toxicity, and Chemistry. In *Chromium in Plants and Environment* (pp. 43-62). Cham: Springer Nature Switzerland.

Waheed, K., Nawaz, H., Hanif, M. A., & Rehman, R. (2020). Tomato. In *Medicinal Plants of South Asia* (pp. 631-644). Elsevier.

Wang, n., wang, x., chen, l., liu, h., wu, y., huang, m., & fang, L. (2023). Biological roles of soil microbial consortium on promoting safe crop production in heavy metal (loid) contaminated soil: a systematic review. *Science of The Total Environment*, 168994.

Wu, X., Nawaz, S., Li, Y., & Zhang, H. (2024). Environmental health hazards of untreated livestock wastewater: Potential risks and future perspectives. *Environmental Science and Pollution Research*, *31*(17), 24745-24767.

Yaashikaa, P. R., Kumar, P. S., Jeevanantham, S., & Saravanan, R. (2022). A review on bioremediation approach for heavy metal detoxification and accumulation in plants. *Environmental Pollution*, *301*, 119035.

Yahaya, S. M., Mahmud, A. A., & Abdu, N. (2023). The use of wastewater for irrigation: pros and cons for human health in developing countries. *Total Environment Research Themes*, *6*, 100044.

Yan, L. J., & Allen, D. C. (2021). Cadmium-induced kidney injury: Oxidative damage as a unifying mechanism. *Biomolecules*, *11*(11), 1575.

Yang, L., Zhang, Y., Wang, F., Luo, Z., Guo, S., & Strähle, U. (2020). Toxicity of mercury: Molecular evidence. *Chemosphere*, *245*, 125586.

Yu, H., Chen, F., Ma, J., Khan, Z. I., Hussain, M. I., Javaid, I., ... & ur Rahman, M. H. (2022). Comparative evaluation of groundwater, wastewater and canal water for irrigation on toxic metal accumulation in soil and vegetable: Pollution load and health risk assessment. *Agricultural Water Management*, *264*, 107515.

Yu, H., Chen, F., Ma, J., Khan, Z. I., Hussain, M. I., Javaid, I., ... & ur Rahman, M. H. (2022). Comparative evaluation of groundwater, wastewater and canal water for irrigation on toxic metal accumulation in soil and vegetable: Pollution load and health risk assessment. *Agricultural Water Management*, *264*, 107515.

Yu, H., Chen, F., Ma, J., Khan, Z. I., Hussain, M. I., Javaid, I., ... & ur Rahman, M. H. (2022). Comparative evaluation of groundwater, wastewater and canal water for irrigation on toxic metal accumulation in soil and vegetable: Pollution load and health risk assessment. *Agricultural Water Management*, *264*, 107515.