Heliyon 9 (2023) e17359

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Review article

Potential ecological risk assessment of heavy metals associated with abattoir liquid waste: A narrative and systematic review

Solomon Nandomah, Isaac Kow Tetteh *

Department of Environmental Science, Kwame Nkrumah University of Science and Technology, Kumasi, Ghana

ARTICLE INFO

Keywords:
Ecological risk
Abattoir liquid waste
Heavy metals
Regulations
Meta-analysis
Meta-regression
Narrative review
Systematic review

ABSTRACT

The article presents a narrative and systematic review of the potential ecological risk assessment of heavy metals associated with abattoir liquid waste for knowledge advancement. The narrative review primarily focused on (i) An overview of abattoir operations; (ii) Characteristics of abattoir liquid waste; (iii) Heavy metals in the liquid waste and their health effects; (iv) Environmental impacts of abattoir liquid waste; and (v) Potential ecological risk index (RI) methodology. These provided essential literature for the systematic review. Using exclusive/inclusive criteria, 15 abattoirs that satisfied the eligibility criteria, all located in Nigeria, were used for the systematic review with meta-analysis/meta-regression. Comparative multiple linear meta-regression analyses were used to quantify the heterogeneity variances between the abattoirs based on standardized RIs (SRIs; effect sizes) using eight tau (τ) estimators in R metafor. The effects of three standardized moderators— number of metals, metal concentrations, and relative distances between the abattoirs and a pristine environment, Gashaka-Gumti National Park (GNP), were also analyzed. The Sidik-Jonkman (SJ) estimator yielded a realistic output, and the current research findings were based on this estimator. The Cochran statistic (QE) suggested an absence of heterogeneity($p>0.99$). Between-study heterogeneities, quantified by H^2 (1.05), I^2 (4.76%), and τ^2 (0.0032 ± 0.0032 (SE)) statistics were very low, practically suggesting complete homogeneity. The moderators accounted for R^2_* of 95.73% of the total explanatory capacity of the model. The beta coefficients of the moderators and intercept were significant (p-values: 0.009–0.0004). While the first two moderators showed in-phase relations with the SRIs, the third indicated an out-of-phase relation. Such links suggest the existence of abattoir-environment interactive processes. Although the abattoirs are spatially distinct and independent, their operations showed evidence-based homogeneity and posed high ecological risks. Hence, environmental legislation should be strictly enforced while ensuring human settlements are sited reasonably from abattoirs.

Abbreviations: BOD, Biological Oxygen Demand; COD, Chemical Oxygen Demand; c.w.e, carcass weight equivalent; DNA, Deoxyribonucleic acid; DO, Dissolved Oxygen; EFSA, European Food Safety Authority; EPA Victoria, Environment Protection Authority Victoria; FAO, Food and Agricultural Organization; FEEDAP, Panel on Additives and Products or Substances Used in Animal Feed; LCC, Lower Continental Crust; LGB, Local geochemical background; OECD, Organization for Economic Co-operation Development; RDA, Recommended Daily Allowance; RDI, Recommended Dietary Intake; RGB, Reference geochemical background; SDG, Sustainable Development Goal; TN, Total Nitrogen; TOC, Total Organic Carbon; TP, Total Phosphorus; TSS, Total Suspended Solids; UCC, Upper Continental Crust; US EPA, United States Environmental Protection Agency; WHO, World Health Organization.

* Corresponding author.
E-mail address: iktetteh.cos@knust.edu.gh (I.K. Tetteh).

https://doi.org/10.1016/j.heliyon.2023.e17359
Received 2 August 2022; Received in revised form 13 June 2023; Accepted 14 June 2023
Available online 15 June 2023

1. Introduction

The meat processing industry uses over 62×10^6 m^3 of water annually, representing over 29% of all freshwater used in agriculture globally [1,2] and, as a result, produces large volumes of liquid waste. However, the amount of water used per killed animal depends on the animal and the technique used in each business. The water usage ranges from 1.0 to 8.3 m^3, with about 0.4–3.1 m^3 lost as effluent for each slaughtered animal [3].

According to the FAO's agricultural outlook for the next decade (2020–2029) [4], meat consumption is expected to increase by 12% from the base period estimate of 325,246 kt c.w.e in 2017–2019 to 365, 149 kt c.w.e. by 2029. By extension, meat supply is expected to increase about the same margin, with a projected increase of 40 Mt c.w.e by 2029 with an estimated amount of 366,436 kt c.w.e., when compared to the base period of 2017–2019 (326,729 kt c.w.e) [4]. This projection is due to rising population and consumption levels [5]. As meat production and consumption rise, more animals need to be slaughtered. Likewise, more abattoirs will be built, or existing facilities will be expanded to meet the demand [6], leading to increased liquid waste generation [2].

Abattoir liquid waste is a typical pollution source with severe environmental trepidations [7]. Therefore, the US EPA considers abattoir liquid waste among the most environmentally harmful industrial wastewater [2]. Wastewater generated from the operations of abattoirs is mainly from activities such as washing carcasses after hair and hide removal and after evisceration, rendering, washing of equipment, paunch handling, trimming, and scalding [8,9].

Blood not recovered, viscera, gut content, bone, urine, excrement, soft tissue destroyed during trimming and cutting, dissolved solids, solubilized fat, and cleaning and sanitizing agents are among the constituents of abattoir liquid waste [8–10]. High levels of salts, phosphates, nitrates, heavy metals, bacteria, viruses, and other microbes are frequently associated with abattoir liquid waste [11]. The vast majority of abattoir liquid waste is discharged into rivers and the immediate surroundings of the abattoir [9,12]. The untreated liquid waste also contains high levels of organic N, decomposing into ammonia, a direct toxicant to aquatic life. The DO content of the abattoir liquid waste is reduced by the microbes, resulting in foul odors and water darkening [8].

Several authors have reported heavy metals in abattoir liquid waste [9,13–15]. The metals pose significant environmental dangers to aquatic life and humans. Due to their persistence in the environment, toxic effects, the propensity to accumulate in organisms and cause food chain amplification, and the fact that they are non-degradable, heavy metal toxicity has many significant health consequences [16]. However, there is a dearth of information on their potential ecological risks to ecosystem integrity. This review is, therefore, justifiable as the authors identified this literature gap and explored it for knowledge advancement. The narrative review is complemented by a systematic review [17–19] to make the paper more relevant regarding novelty, contribution to knowledge, and knowledge synthesis.

The paper, which aims at reviewing the potential ecological risk assessment of heavy metals detected in abattoir liquid waste, is structured along the two review types. It commences using data triangulation to select relevant literature for the two tasks. The narrative component primarily focused on the following: (i) An overview of the abattoir operations resulting in liquid waste generation; (ii)The compositional characteristics of abattoir liquid waste, as well as the most frequently occurring heavy metals with human health and environmental impacts; and (iii) An overview of potential ecological risk index (RI) methodology. The outcome set the tone for a systematic review employing meta-analysis/meta-regression techniques for analyzing potential ecological risks associated with spatially distinct and operationally independent 15 abattoirs in the same geographical location. The results necessitated an overview of regulatory measures governing liquid waste discharge to urge government agencies, policy-makers, private sectors, and other actors to be more proactive in environmental protection. It concludes, among other things, by invoking a possible future debate on ambivalence toward abattoir operations, viewed from the authors' standpoint, in the context of SDGs.

2. Selection of relevant literature

To efficiently review the extent of ecological risks that abattoir operations pose to humanity as well as the environment, a literature search was done across several search engines (for example, Google Scholar, Crossref, PubMed, Semantic Scholar, etc.) using Harzing's Publish or Perish version 8.2.3944.8118, with the following keywords: ecological risk assessment, potential ecological risk index (RI), abattoir, abattoir liquid waste, abattoir wastewater, slaughterhouse wastewater, effluent discharge, discharge limits, meta-regression, meta-analysis, systematic review, heavy metals, environmental impact, and discharge regulation. The search result was limited to 1000 articles, excluding citation records and patents. The publication year was not limited to any specific year to get all the necessary information on the subject matter. However, results obtained from the literature search were scrutinized, and the appropriate journals that satisfied the scope of this review were used. The review is, therefore, based on credible journals and articles obtained through various literature searches and data triangulations [20,21]. In all, 96 credible pieces of literature relevant to the scope of this review were reviewed and effectively scrutinized.

3. Narrative review

3.1. An overview of abattoir operations

Receiving and holding livestock; slaughtering and dressing of livestock carcasses; chilling of carcasses and their products; boning and packaging of carcasses; freezing of carcasses; rendering and drying of skins; waste treatment; and finally, transportation of processed meat and by-products are all common abattoir operations [22,23].

Most slaughterhouses encompass a pen where animals are temporarily kept while waiting to be slaughtered. The final selection of an animal to be sent to the killing bay occurs here. Dung, animal feeds, and urine are major wastes generated in the holding pen [24]. Slaughtering is a term used when the throat of an animal is slit and usually proceeds with bleeding. Bleeding allows blood to flow out of a blood vessel or artery in the neck after severed. As a result of this process, the animal dies. The skin is removed after the animal has been slain. Skinning prepares the muscular tissues beneath the skin for consumption, fur production, or tanning. The carcasses are washed and prepared for evisceration and splitting once skinned. Blood, wastewater, bone, undigested food, dung, and semen are the significant waste generated during slaughtering [24].

The biochemical and structural modifications in muscles within the first 24 h after death significantly impact meat's final quality and wholesomeness. They are affected by the chilling mechanisms that carcasses undergo following slaughter. Chilling animal carcasses ensures food safety, extends shelf life, and prevents shrinkage [25]. The most prevalent chilling procedures are conventional carcass chilling and spray chilling. Spray chilling includes administering cold water to carcasses during the early stages of death [25], which is different from using cool, unsaturated air flowing through chill chambers [26]. Abattoir waste, both solid and liquid, is generated during the various stages of operations. The characteristics of liquid waste, an important segment of this review, are described in the next section.

3.2. Characteristics of abattoir liquid waste

Abattoir liquid waste is deemed toxic worldwide due to its relatively complex composition of lipids, proteins, fibers, high organic content, pathogens, and pharmaceuticals for veterinary purposes [2]. The effluent also contains significant suspended materials such as fats, greases, hairs, feathers, meats, dung, grits, undigested feed, blood, and about 80% freshwater [8].

Most organic load in abattoir liquid waste originates from blood and lipids [11]. Blood from the abattoirs comprises about 18% protein and is considered a significant animal by-product rich in protein [23]. The existence of substantial amounts of proteins in abattoir liquid waste renders its characteristic nasty odors [1].

Abattoir liquid waste also has high BOD, chlorides, dry residues, detergents, and disinfectants. Blood is the major dissolved pollutant in abattoir liquid waste, with the highest COD value (375,000 mg/L) [1,27]. Blood also contributes significant N to liquid waste [11]. The liquid waste may contain pathogens and eggs of intestinal parasites and helminths, such as *Ascaris,* which originate primarily from blood, stomach, and intestinal mucus [1].

Several studies have also reported the presence of heavy metals in abattoir liquid waste [1,8,9,28]. Due to the extensive range of pollutant loads in the waste, abattoir effluents are mainly assessed using bulk parameters [2]. Typical characteristics of abattoir liquid waste compiled from different literature are summarized in Table 1.

3.3. Heavy metals commonly reported in abattoir liquid waste and their health effects

Heavy metals commonly arising from abattoir operations and reported in the liquid waste include copper (Cu) [8], zinc (Zn), iron (Fe), manganese (Mn), chromium (Cr), nickel (Ni), cadmium (Cd), and mercury (Hg) [7, 9, 27], and lead (Pb) [15, 28]. With accelerated global environmental change primarily driven by anthropogenic activities, resulting in the disturbances of ecological health, ecosystem health, ecosystem integrity, wildlife health, and human environmental health [34], the effects of heavy metals in abattoir liquid waste are inextricable. The toxicological profiles of overexposure to heavy metals and their consequences, including mutagenicity, carcinogenicity, teratogenicity, genotoxicity, immunosuppression, and physiological and biochemical disorders, cannot be understated. Heavy metals enter the human system through ingestion, inhalation, and dermal absorption. However, according to Shi et al. [35], ingestion and dermal contact are the most common routes for these metals in water and, by extension, abattoir liquid waste. For instance, heavy metals may be introduced into the human system by ingesting partially treated municipal water supply from water sources polluted by untreated abattoir liquid waste. This section presented a brief narrative of the effects of the aforementioned heavy metals with particular reference to human health, highlighted in Table 2.

3.3.1. Copper (Cu)

Cu is in Group 11 of the periodic table. It is a trace element found in high concentrations in the human brain, liver, kidney, bone, and muscle, requiring 1–100 mg/day by an adult [36]. Bone and muscle account for more than 50% of the metal in the body. Cu is

Table 1
Typical characteristics of abattoir liquid waste reported in the literature.

Parameters	Untreated abattoir liquid waste from different sources							
	A	B	C	D	E	F	G	H
pH	8.4–9.4	6.3–8.2	7.3 ± 0.43	8.0–8.5	4.9–8.1	7.15–7.68	–	6.92–8.18
Turbidity	–	–	566.66 ± 28.86	75–511	200–300	–	–	–
TSS (mg/L)	14,840–15530	730–2500	3835.33 ± 2072.57	1253–1413	0.1–10,000	–	230–760	1498–6803
COD (mg/L)	9200–9400	5380–8400	11546.67 ± 4130.19	114–1033	500–16,000	2000–10000	1190–2800	947–2566
BOD (mg/L)	950–1200	2978–6422	3980 ± 1055.13	–	150–8500	–	610–1150	–
TOC (mg/L)	–	–	–	50–328	50–1750	–	–	–
TN (mg/L)	–	288–740	–	82–127	50–850	42–227	150–260	–
TP (mg/L)	–	52–301	202 ± 37.72	8–23	25–200	23–129	–	142–180

A - [29], B - [1], C - [30], D - [3], E - [31], F - [32], G - [33], H - [28].

found in various plant and animal diets [37]. Therefore, it is unsurprising that several studies have detected this metal in abattoir liquid waste [13,38,39].

Cu has both antioxidant and prooxidant properties. It scavenges or neutralizes free radicals as an antioxidant, potentially reducing or preventing part of the harm they cause. When it functions as a prooxidant, it causes free radical damage to the tissues [40]. While Cu is required for many proteins as a catalytic cofactor in redox chemistry, excessive amounts of free Cu ions can injure biological components (Table 2).

3.3.2. Zinc (Zn)

Zn, Cd, and Hg occur naturally and belong to Group 12 of the periodic table. Compared to Cd and Hg and several other metal ions with similar chemical properties, Zn has comparatively low toxicity and relatively infrequent adverse effect on human health [41]. It is prevalent in the air, water, and soil. However, its abnormally high environmental concentrations are primarily attributed to anthropogenic activities. It is mainly employed in industrial processes such as mining, coal and waste combustion, and steel production.

While Zn deficiency can cause several disorders, such as pancreatitis, metabolism errors, and arteriosclerosis, overexposure is also detrimental. For instance, Zn is hazardous to fetuses and infants when exposed to large quantities through their mothers' blood and milk. Other human health impacts associated with exposure to Zn are summarized in Table 2.

3.3.3. Iron (Fe)

Fe is the most abundant metal in the earth's crust [42] and belongs to Group 8 of the periodic table. The biological properties of Fe are dependent on redox interconversions between the ferrous (Fe(II)) and ferric (Fe(III)) forms [43]. Fe is found in meat, whole grain products, potatoes, and vegetables. The human body absorbs Fe from animal meals faster than from plant foods. Hemoglobin, the red pigment in our blood that delivers oxygen throughout our bodies, requires Fe [44]. Human health issues associated with overexposure to Fe are presented in Table 2.

3.3.4. Manganese (Mn)

Mn is a trace element that all animals require in their diet. It is located in Group 7 of the periodic table. While it can be inhaled from the air, human exposure to the metal is mostly through diet. Mn can be found in various foods, including grains and green leafy vegetables [45]. Mn aids bone development, controls metabolic activities such as protein and energy metabolism, and protects cells from free radicals and glycosaminoglycan production in humans and animals [46].

The presence of Mn in liquid effluent from slaughtering operations has been reported in several investigations [15, 47]. Mn toxicity and associated human health risks (Table 2) have been documented [46].

3.3.5. Chromium (Cr)

Cr is a chemical element belonging to Group 6 of the periodic table. It is an essential nutrient for human health, but too much can be harmful. As a result of many human activities over the last few decades, its pollution, particularly in the hexavalent chromium form, has increased in terrestrial and aquatic ecosystems [48]. Depending on pH, redox potential, and the occurrence of natural reducing agents, the most common oxidation states of Cr found in water are the trivalent Cr (III) and hexavalent Cr (VI) forms. The most significant industrial contributors to Cr emissions in water are thermal power plants and other combustion facilities, followed by waste

Table 2
Toxic effects of heavy metals on human health.

Metals	Toxic effects on human health
Cu	Excessive exposure to Cu causes oxidative stress, DNA damage, and a reduction in cell growth. In addition, ingesting more than 1 g of copper sulfate causes poisoning symptoms [36]. It also causes skin and mucous irritation, liver disease, and hemolytic anemia [57].
Zn	Excessive doses of Zn may cause stomach pain, nausea, and vomiting. Lethargy, anemia, and dizziness are also associated with excessive intake of Zn [41]. Excessive zinc chloride exposure might cause respiratory problems.
Fe	Overexposure to Fe can induce conjunctivitis, choroiditis, and livers, retinitis. Siderosis, or benign pneumoconiosis, can be caused by chronic inhalation of large amounts of iron oxide fumes or dust. Inhaling excessive quantities of iron oxide may raise the risk of lung cancer in pulmonary carcinogen-exposed workers [44].
Mn	Mn causes neuromotor deficits like Parkinson's disease [59]. It also causes pulmonary inflammation, systemic, immunological, neurological, reproductive, developmental, genotoxic, and carcinogenic consequences in exposed persons [46].
Cr	Cr poisoning can have profound implications for respiratory, cardiovascular, gastrointestinal, hematological, hepatic, renal, and neurological systems [60].
Ni	Long-term exposure to Ni can lead to weight loss, heart and liver damage, and skin irritation [14]. It may also lead to lung, nose, and cancer of the larynx and prostate. It may also result in some congenital disabilities, asthma, and allergic reactions [57].
Cd	Cd can affect the kidneys, livers, skeletal and cardiovascular systems and cause eyesight and hearing loss, even at low concentrations. It also disrupts steroidogenesis and causes difficulties with the menstrual period and reproductive hormones, puberty and menstrual irregularity, stillbirths, preterm birth, and low birth weight [51].
Hg	Metallic Hg causes malfunctioning of the thyroid, breast, heart, muscle, adrenal gland, liver, kidney, skin, sweat gland, pancreas, enterocyte, lung, salivary gland, testis, and prostate gland. Hg poisoning can cause many human health problems, including neurological, renal, gastrointestinal, genetic, cardiovascular, and developmental abnormalities and mortality [61].
Pb	In humans, high exposure levels to Pb can cause biochemical problems like hemoglobin synthesis problems, impact the kidneys, joints, gastrointestinal system, and reproductive system, and cause acute and chronic nervous system impairment [58].

and wastewater treatment plants.

Interestingly, several studies have reported the presence of Cr in abattoir liquid waste [7, 9, 14, 49]. The primary source of public concern is the detrimental consequences of Cr (VI) compounds on humans, animals, plants, and microbes. Human health concerns range from skin irritation to DNA damage and cancer formation depending on the dose, intensity, and duration of exposure [50] and are summarized in Table 2.

3.3.6. Nickel (Ni)

The chemical element, Ni, is a trace metal that belongs to Group 10 of the periodic table. It is required for animal nutrition. However, several studies have reported the detection of Ni in abattoir liquid waste [9,14,39,49]. According to Elemile et al. [49], animal Ni is obtainable through feeding on Ni-containing feeds and water, and the metal finds its way into abattoir liquid waste via excretion and egestion.

Ni is necessary in modest amounts, but excessive intake can harm human health. Short-term exposure to the metal does not appear to produce any health effects in humans. Long-term exposure, however, may lead to detrimental health effects, as presented in Table 2.

3.3.7. Cadmium (Cd)

Physically and chemically, Cd is a soft, silvery-white metal akin to Zn and Hg of Group 12 of the periodic table. It is a highly poisonous heavy metal without biological use [51]. According to the WHO [52], although the metal is generally found in low quantities in the environment, human activities such as smelting and refining Cu and Ni, burning fossil fuels, and using phosphate fertilizers have resulted in its significant amounts. The metal is also found in nonferrous metal smelters and electronic waste recycling facilities [51].

Food is the principal source of human environmental exposure to Cd [52]. It has been reported that the kidneys and livers of mammals fed with Cd-containing diets house the most significant levels of this metal [52]. Various crops and aquatic animals can assimilate this metal in soil and water sources, accumulating it in the food chain. Several studies have identified the metal in abattoir liquid waste [9,13,39]. The human health effects of Cd are highlighted in Table 2.

3.3.8. Mercury (Hg)

Hg enters the environment in the form of metallic Hg. The combustion of fossil fuels, burning of wastes, smelting, and mining contribute to about 80% of the aggregate, with volcanoes and forest fires accounting for the rest [53]. Many countries have designated Hg as a dangerous priority metal and thus have, through the worldwide Minamata Convention, signed an agreement to lower global anthropogenic emissions aimed at addressing various environmental and health issues related to the metal [54]. Mohammed et al. [9] reported the presence of Hg in abattoir liquid waste. From another perspective, Sakakibara et al. [53] aver that the Hg that remains in the terrestrial food chain could be a source of Hg pollution in animals. Hg in abattoir liquid waste can be attributed to animals' diet, including contaminated grass or other plants, drinking water, and small amounts of soil. According to Sakakibara et al. [53], this is the primary route of metal deposition in their kidneys, liver, bones, hair, and blood. The effects of chronic human exposure to Hg are indicated in Table 2.

3.3.9. Lead (Pb)

Pb is a chemical element located in Group 14 of the periodic table. It is one of the most environmentally hazardous heavy metals. It has been employed since ancient times due to its vital physicochemical characteristics. Pb and its compounds are commonly found in leaded gasoline and other industrial operations, including Pb smelting and combustion, pottery, Pb-based painting, battery recycling, Pb-containing pipes, metal grids, boat building, the armaments industry, pigments, and book printing [55].

Numerous studies have widely reported Pb in abattoir liquid waste [9, 13, 14, 56]. It builds up in the bone marrow where red blood cells are made; it alters porphyrin metabolism and creates symptoms similar to acute intermittent anemia [57]. The biological effects of Pb exposure in humans depend on the amount and length of exposure. At varying doses, different consequences occur, with a growing fetus and baby being more susceptible than adults, as with all other toxicants. The environmental health effects of Pb have been summarized in Table 2.

3.4. Environmental impacts of abattoir liquid waste

Due to the complex and detrimental composition of abattoir liquid waste, it is almost challenging to treat, and it is most often discharged untreated into waterways and drainage [7]. According to Magaji & Chup [39], untreated abattoir liquid waste that enters water bodies contributes substantial amounts of N, P, BOD, and other nutrients, polluting the receiving environment.

The release of liquid waste into water bodies impacts water quality, particularly since it has highly biodegradable organic compounds that tend to reduce DO, which can cause aquatic life to perish due to hypoxic and, in extreme cases, anoxic conditions. Macronutrients like N and P can also cause eutrophication. Excessive algal growth and eventual breakdown occur when bacteria decompose a large biomass of dead algae. As a result of the depleting DO levels, algal mineralization may result in the degeneration of aquatic life [2]. Other environmental challenges, such as odorous environment and water pollution issues [62] and increased incidence of waterborne diseases [63], have been attributed to abattoir operations. Sulfur dioxide, a preservative used in meat processing in some abattoirs, raises sulfur levels in the liquid waste and contributes to the obnoxious odor of the abattoir environment [8]. Heavy metals found in abattoir liquid waste can affect the aquatic ecosystem, soils, and animals in various ways. The disturbances in the aquatic ecosystem include, among other things, the death of aquatic organisms, their combined effects with eutrophication, acute/chronic toxicity, habitat destruction due to sedimentation, and changes to water chemistry. For instance, high quantities of Zn in industrial wastewater have contaminated the water supply. Rivers dump Zn-polluted sludge on their banks, which contributes to sedimentation. Zn can raise the acidity of water and may also build up in the bodies of fish that live in Zn-contaminated streams [64]. Heavy metal-laden soils, especially in riparian communities, degrade the quality and quantity of plant food and interfere with nutrient uptake, as well as physiological and metabolic processes. For example, plants with too much Pb show signs of toxicity, such as stunted development, chlorosis, and root system darkening. Root growth suppression appears to be caused by Pb, which inhibits cell division. Pb inhibits photosynthesis, modifies mineral nutrition and water balance, changes hormone levels, and changes the shape and permeability of the plasma membrane [58]. Heavy metal effects on animal health, with particular reference to humans, have been presented in the previous section.

3.5. Environmental risk assessment

Risk assessment is used in various industries, organizations, and sectors, including engineering, commerce, public health, medicine, natural resource management, irrigation, and biosecurity [65]. Various risk assessment tools can be used in assessing environmental parameters depending on the objective of the approach. Enrichment factor, health risk assessment [66], risk quotient [67], hazard quotient [68], and ecological risk assessment [69] are among the most commonly used risk assessment tools based on environmental parameters of concern.

Environmental risk assessment, according to EPA Victoria [65], “evaluates the interactions between environmental values, the stressors to these, and management actions for protecting the values.” However, this section focuses on Hakanson’s RI, as it can be applied in several fields of research, including but not limited to biological toxicology, ecology, and environmental chemistry [69].

3.5.1. Overview of potential ecological risk assessment of heavy metals

The RI is a diagnostic tool introduced by Hakanson [69] to investigate the degree of risks posed by heavy metals in the environment [70]. Banu et al. [71] described RI as a diagnostic tool to identify which areas in drainages, reservoirs, or substances need special attention in risk assessment. However, it effectively evaluates the ecological risks caused by heavy metals [72]. This subsection reviews the RIs posed by heavy metals in abattoir liquid waste.

According to Liao et al. [73], RI indicates ecological responsiveness and susceptibility to harmful heavy metals and assesses environmental danger. The target heavy metal type, concentration, toxicity coefficient, and the water body’s sensitivity to heavy metals are all considered.

RI is determined using Equation (1) [69] as follows:

$$\mathrm{RI} = \sum_{i=1}^{n} E_r^i \quad (1)$$

RI, n, and E_r represent the total potential ecological risk of heavy metals, the number of heavy metals under investigation, and the monomial potential ecological risk factor, respectively.

E_r is, however, determined using Equation (2) [69] below.

$$E_r^i = T_r^i x C_f \quad (2)$$

where T_r^i is the individual heavy metal toxicity response coefficient (Cd = 30, Cr = 2, Pb = 5, Ni = 5, As = 30, Cu = 10, Zn = 1, Hg = 40, Mn = 1) and C_f being contamination factor [70,72,74,75].

According to Hakanson [69], C_f accounts for the contamination of a single element, and it is determined based on Equation (3) as follows:

$$C_f^i = \frac{C_{0-1}^i}{C_n^i} \quad (3)$$

$C_{0\text{-}1}^i$ and C_n^i represent the heavy metal content and the preindustrial reference value of the metal, respectively. The preindustrial reference values for Cd, Cr, Pb, Cu, Zn, and Hg in sediments are 1, 90, 70, 50, 175, and 0.25, respectively. Also, the natural background concentration of Cd, Cr, Pb, Cu, Zn, and Hg in freshwater are 0.008, 0.00018, 0.005, 0.01, 0.01 and 0.00008 [69], respectively. Table 3 shows the interpretation of C_f values based on Equation (3).

Preindustrial reference values for most metals had not been covered by Hakanson [69]; hence, several other reference values are used to determine pollution indices. RGB and LGB are the two central reference values that estimate pollution indices. RGB, which

Table 3
Interpretation of C_f values.

C_f value	Contamination
<1	low contamination
1–3	moderate contamination
3–6	considerable contamination
>6	very high contamination

includes concentrations of trace metals in the UCC, LCC, or the average heavy metal content on the worldwide surface horizon available in Kabata-Pendias & Pendias [76], may be used to investigate pollution indices. However, RGB values do not often present natural variability, so using only RGB makes it challenging to appreciate natural influences and other trace metal contamination from anthropogenic sources. Nonetheless, using RGB gives a global perspective to heavy metal assessment as it provides adequate information concerning the appreciation of environmental quality evaluation at a global scale beyond local scale comparisons [77]. However, the use of LGB, the heavy metal concentration in the most pristine or unpolluted sites, is recommended, especially when anthropogenic impact and high contamination levels are suspected [77]. Fe is a necessary component of all biological systems; no toxic-response factor has been ascribed to it, and thus, no ecological risk factor [78]. According to Soliman et al. [72], E_r values less than 40, in the ranges of $40 < E_r \leq 80$, $80 < E_r \leq 160$, $160 < E_r \leq 320$, and greater than 320, are assigned low, moderate, appreciable, high, and serious risks, respectively. Similarly, when RI values are less than 150, in ranges of 150–300, 300–600, and 600 and above, the risk levels are presumed low, moderate, high, and significantly high, respectively.

This subsection also provided inputs for conceiving a solid framework for a systematic review employing meta-analysis/meta-regression techniques to analyze potential ecological risks associated with 15 abattoirs. The abattoirs are spatially distinct and operationally independent, located in Nigeria.

4. Systematic review with meta-analysis/meta-regression

4.1. Introduction

A systematic review gathers all relevant studies concerning a specific topic and methodology and evaluates their findings. It is commonly referred to as research about research. The quality of research is assessed throughout the systematic review process, and the results of the studies are then the subject of meta-analysis/meta-regression based on the quality of the investigations [17–19].

According to Ahn & Kang [17], meta-analysis is a "valid, objective, and scientific method" of evaluating and integrating different results to aid in the extraction of accurate, high-quality information from a wide range of available data. The technique provides a standardized method for analyzing prior findings in the literature on a particular topic [18]. It should be emphasized that some research has been conducted to evaluate heavy metal levels in abattoir liquid waste (a few results are summarized in Table 6). Unfortunately, RI research on heavy metals associated with abattoir liquid waste is rarely conducted. Due to this literature gap, a systematic review with meta-analysis/meta-regression [17–19] is deemed appropriate for computing the risks posed by abattoir for knowledge advancement. RI estimations are traditionally based on the method proposed by Hakanson [69]. However, the requisite data for meta-analysis and meta-regression are prone to systematic biases and methodological diversities. It, therefore, demands appropriate models to adequately handle the heterogeneity variance of the effect size differences based on relevant moderators [79]. The study sought to (i) quantify standardized RIs (SRIs; effect sizes) of 15 abattoirs in a specified geographic location using a mixed-effects model type; and (ii) use appropriate moderators, test for heterogeneity, and quantify uncertainties associated with meta-analysis/meta-regression. The study also comparatively evaluated the eight tau (τ) estimators in the R metaphor.

4.2. Methods

4.2.1. The inclusion criteria and study area

The inclusion criteria used for selecting the abattoirs were as follows: (i) Abattoirs operating in similar geographical locations; (ii) Abattoirs lacking wastewater treatment facilities; and (iii) Published articles in which the influent/drainage (point-source) strictly originated from the abattoir operations. These allowed for unbiased analysis by targeting various metal levels to assess their potential

Table 4
Study area locations.

Abattoir	Geographic locations	Abattoir distance (km) from GNP
Minna Central	6°01′ 00″ N, 9°04′59″ E	352.85
Kashua Shanu[a]	11°51′36″ N, 13°10′34″ E	485.97
Tudun Wada	10°30′33″ N, 7°24′25″ E	559.65
Egbu	5°28′25″ N, 7°03′11″ E	567.23
Ahiara Mbiase	5°31′51″ N, 7°17′10″ E	538.51
Amakohia Ikeduru	8°38′58″ N, 10°17′39″ E	551.47
Kasuwan Shanu[b]	11°51′36″ N, 13°10′34″ E	485.97
Anantigha	4°55′15″ N, 8°19′25″ E	480.50
Nkonibs	5°00′44″ N, 8°20′31″ E	448.08
Iworoko	7°41′33″ N, 5°15′18″ E	706.71
Ikere	7°29′45″ N, 5°13′48″ E	711.39
Atikankan	7°37′05″ N, 5°13′15″ E	708.14
Iwofe	4°48′35″ N, 6°57′31″ E	608.67
Rumuodomaya	4°52′07″ N, 6°59′34″ E	583.55
Trans-Amadi	4°48′26″ N, 7°02′18″ E	604.46

Source: Authors (2023). [a] [13] Kashua Shanu in 2010; [b] [9] Kasuwan Shanu in 2020. These two are the same abattoir facilities reported by different authors.

risks before the wastewater was discharged downstream. The exclusion of downstream effluent data from articles was deemed appropriate since such data would represent both point-source and nonpoint-source pollution. Also, such data would not be the true effect sizes associated with the abattoir operations.

Out of the 96 critically scrutinized articles in Section 2, only eight satisfied the eligibility criteria and consisted of 14 abattoirs. In a set of three articles [56,80,81], each contains three datasets from three different abattoirs making a total of nine, while Agbor & Antai [82] reported data from two different abattoirs. Two articles [14,15] reported a dataset each from a different abattoir. The 14th abattoir had two different research articles (data) published in different years by different authors [9,13], thereby increasing the sample size by one (i.e., n = 15), as depicted in Tables 4, 5, 6, and 7. Therefore, we regard the RIs, which are surrogates of the abattoirs, to be 15.

The abattoirs are all found in Nigeria, and their respective geographic point coordinates are displayed in Table 4. Their spatial distributions and Gashaka-Gumti National Park (GNP) are shown in Fig. 1.

GNP is the largest natural park in Nigeria. It spans 6731 sq km of untamed terrain. The park's name is drawn from two of the oldest and most storied communities in the area Gashaka village in Taraba State and Gumti village in Adamawa State. By Federal Decree, Gashaka and Gumti Game Reserves were amalgamated into GNP in 1991. Its distinguishing features are the steep, densely forested slopes, deep valleys, sheer escarpments, and swift-moving rivers that make up this difficult topography [83].

GNP has a remarkably diverse range of fauna because of the sheer number of varied environments there. The park is a complex mosaic of montane grasslands, savanna woods, swamps, lakes, vital rivers, lush lowland rainforests, and montane rainforests dotted with ferns and orchids [83].

4.2.2. Timescale, assumptions, and research questions

The eligible articles used for the systematic review spanned from 2010 to 2021. The following assumptions were made for the scope and analysis framework: (i) The 15 abattoirs are spatially, operationally, and mutually independent; (ii) The quantities of liquid waste generated and the trace metal levels are fundamentally different; (iii) The number of trace metals together with their levels are key determinants of their contributions to the RIs; (iv) The abattoirs are distant from relatively unpolluted sites; (v) Mixed-effects model type — precisely one which subsumes random-effect model is deemed appropriate due to intra- and between-study heterogeneities.

A set of research questions outside the scope of the articles that satisfied the eligibility criteria but deemed to have intellectual merit in the current study are as follows: (i) Will the heterogeneous compositional characteristics of the liquid waste provide an adequate basis for quantifying monomial ecological risks (E_{rS}) , the RIs, and hence the effect sizes? (ii) Does the number of metals relate to the effect sizes? (iii) Do the distances of the abattoirs from a relatively unpolluted reserve or conserved site have any link to the effect sizes? (iv) How well do the moderators explain the level of heterogeneity variance of the effect sizes? (v) What are the uncertainties associated with the effect size estimations? These questions are addressed in the subsequent sections, using standard RI methods, meta-analysis, multiple linear meta-regression analysis, heterogeneity tests, and uncertainty analysis.

4.2.3. Multiple linear meta-regression analysis

In a systematic review, meta-analysis/meta-regression has become a popular approach for examining whether research characteristics may contribute to the variability of outcomes among studies [84]. In meta-regression, the variable being predicted is the observed effect size $\widehat{\theta}_k$ of the study (k). Similar to a standard regression model, a meta-regression according to Harrer et al. [79], has the following formula:

$$\widehat{\theta}_k = \theta + \beta x_k + \varepsilon_k + \varsigma_k \tag{4}$$

Table 5
Meta-regression data.

Abattoir	Yi	Sei	Num.met	Conc.	Dist.
Minna Central	3.607151	3.608234	−0.20835	3.605503	−2.03386
Kashua Shanu[a]	−0.05443	−0.07048	2.135615	−0.27132	−0.72396
Tudun Wada	−0.2467	−0.24591	−0.20835	−0.09946	0.00105
Egbu	−0.28616	−0.28501	−0.20835	−0.32354	0.075637
Ahiara Mbiase	−0.28776	−0.28669	−0.20835	−0.32185	−0.20697
Amakohia Ikeduru	−0.29011	−0.28781	−0.20835	−0.33246	−0.07944
Kasuwan Shanu[b]	−0.16391	−0.16931	1.354293	−0.27317	−0.72396
Anantigha	−0.28831	−0.28567	−1.771	−0.19344	−0.77778
Nkonibs	−0.28783	−0.28518	−1.771	−0.12294	−1.0968
Iworoko	−0.27964	−0.2807	0.57297	−0.2516	1.448117
Ikere	−0.27803	−0.27804	0.57297	−0.2349	1.494168
Atikankan	−0.27822	−0.27697	0.57297	−0.24407	1.462188
Iwofe	−0.2846	−0.28123	−0.20835	−0.29942	0.483405
Rumuodomaya	−0.2911	−0.28774	−0.20835	−0.32531	0.236225
Trans-Amadi	−0.29034	−0.2875	−0.20835	−0.31203	0.441979

Source: Authors (2023). [a] [13] Kashua Shanu in 2010; [b] [9] Kasuwan Shanu in 2020. These two are the same abattoir facilities reported by different authors. Yi = Effect sizes (SRIs); Sei = SEs of SRIs

Table 6
Heavy metal concentration in abattoir liquid waste reported from the referenced literature.

Abattoir	Metal Concentration (mg/L)									References
	Cr	Ni	Cd	Fe	Mn	Zn	Hg	Cu	Pb	
Minna Central	0.020	19.100	–	–	–	79.50	–	1.610	0.160	[14]
Kashua Shanu[a]	0.220	0.410	0.740	0.100	0.380	0.250	–	0.270	0.360	[13]
Tudun Wada	–	0.535	–	4.276	0.472	0.703	–	0.095	–	[15]
Egbu	–	0.050	–	0.180	–	0.010	–	0.060	0.0770	[56]
Ahiara Mbiase	–	0.050	–	0.250	–	0.010	–	0.070	0.040	[56]
Amakohia Ikeduru	–	0.020	–	0.090	–	0.010	–	0.020	0.010	[56]
Kasuwan Shanu[b]	0.103	1.543	0.127	0.110	0.130	0.180	0.13	–	–	[9]
Anantigha	–	–	–	1.730	–	–	–	0.0633	0.420	[82]
Nkonibs	–	–	–	2.730	–	–	–	0.060	0.500	[82]
Iworoko	0.130	0.120	0.740	1.440	0.120	–	–	–	0.100	[81]
Ikere	0.080	0.060	1.030	1.620	0.190	–	–	–	0.180	[81]
Atikankan	0.050	0.080	1.120	1.380	0.150	–	–	–	0.100	[81]
Iwofe	0.000	–	0.680	–	–	0.310	–	0.001	0.000	[80]
Rumuodomaya	0.000	–	0.001	–	–	0.130	–	0.001	0.200	[80]
Trans-Amadi	0.000	–	0.000	–	–	0.230	–	0.31	0.130	[80]
Mean*	***0.07***	***2.20***	***0.55***	***1.26***	***0.24***	***8.13***	***0.13***	***0.23***	***0.18***	
Standard deviation (SD)*	***0.06***	***5.96***	***0.45***	***1.34***	***0.15***	***25.08***	***-***	***0.49***	***0.16***	
Standard error (SE)*	***0.02***	***1.88***	***0.16***	***0.40***	***0.06***	***7.92***	***-***	***0.14***	***0.04***	

[a] [13] Kashua Shanu in 2010.
[b] [9] Kasuwan Shanu in 2020. These two are the same abattoir facilities reported by different authors. (–) Not reported in the original article, * Descriptive statistics computed by authors using OriginPro [92].

here θ is the intercept, βx_k is the moderator/predictor, ε_k is the sampling error and ς_k is the between-study heterogeneity. However, in performing multiple linear meta-regression, numerous moderators $(\beta_1 x_{1k} + \ldots + \beta_n x_{nk})$ are used instead of one moderator (βx_k) to account for variation in effects. The model for the multiple meta-regression reported by Harrer et al. [79], therefore, follows the equation:

$$\widehat{\theta}_k = \theta + \beta_1 x_{1k} + \ldots + \beta_n x_{nk} + \varepsilon_k + \varsigma_k \tag{5}$$

The meta-regression in this study was performed using R [85]. The "rma" function in "metafor" is used to achieve this. This function does a random-effects meta-analysis that, when moderators are included, is expanded to mixed-effects meta-regression models [79]. The "rma" function has countless arguments that must be specified in the dataset. The statements defined in the dataset used in this meta-regression analysis included the following: (i) *Yi* –the column in the dataset where the effect size is stored; (ii) *Sei* – the column where the standard error (SE) of the effect size is stored in the dataset; (iii) *data* – the dataset that contains the meta-analysis data (Table 5); (iv) *method* – the τ^2 estimator used; (v) *mods* – the parameters that define the meta-regression model, which is specified with a tilde (~), after which the subsequent predictors are separated with addition sign (+); and (vi) *test* – the test applied for the regression coefficient, is specified, which in this study, was the Knapp-Hartung (knha) method.

4.2.3.1. Selection of moderators and computation of effect sizes. Moderators are vital in understanding effect sizes. Recognizing the philosophical and theoretical underpinnings of the research questions posed previously, the following moderators were considered: (i) Metal concentrations; (ii) Number of metals; (iii) Size of the facilities; (iv) Volume of liquid waste generated per facility; (v) Number of livestock slaughtered/facility/month; and (vi) Relative distances of the facilities from a conserved or protected site. Based on *a priori* assumption, items (i)-(v) were classified as endogenous moderators anticipated to be obtained from the eight articles, whereas item (vi) was classified as an exogenous moderator, which could not be obtained from the articles but from other sources. The exogenous moderator was obtained by empirical measurements using Google Earth (online version), carried out by the authors, and constituted primary data. Regression models are inherently prone to overfitting due to several factors, such as additive predictors that cause overpredictions, multicollinearity issues, and trends in panel data. Specifying a parsimonious model can prevent the curse of dimensionality [86]. Upon screening, endogenous moderators (i) and (ii) were identified and extracted as candidate predictors from the literature (Table 6); the rest [(iii)-(v)] were non-existent. It was envisaged that the three moderators [(i), (ii), and (vi)] could specify a parsimonious model based on statistical tests or assumptions.

Equations (1)–(3) were applied to the metal levels, compiled from the eight articles (Table 6), to compute the E_rs and RIs (Table 7). The effect size (Yi) and SEs of effect size (Sei) data are the standardized RIs (SRIs) and SEs of the SRIs, respectively. The data input for the model were as follows: Yi was the dependent variable, whereas the number of metals analyzed (Num.met) and metal concentrations (Conc.) in each abattoir and the relative distances (Dist.) of the abattoirs from the GNP were used as the moderators. As shown in Table 5, all the meta-regression data were standardized to achieve zero means, unit standard deviations (SDs), and unit variances (0,1,1) to put them on the same scale from which standardized meta-regression was performed.

4.2.3.2. Heterogeneity measures, selection of estimator, and uncertainty analysis. Heterogeneity is a quantitative attribute impacted by the spread and precision of the effect size estimates in a meta-analysis [79]. The term "heterogeneity" has many definitions because it is

Table 7

E_rs and RIs computed from metal concentrations in Table 6.

Abattoir	E_r								Mean RI	SE of RI	RI
	Cr	Ni	Cd	Mn	Zn	Hg	Cu	Pb			
Minna Central	10,000.00	9550.00	–	–	1,391,250.00	–	8050.00	2240.00	284,218.00	276,761.00	1,421,090.00
Kashua Shanu[a]	11,0000.00	205.00	9.25	31.67	4375.00	–	1350.00	5040.00	17,287.00	15,472.00	121,011.00
Tudun Wada	–	267.50	–	39.33	12,302.50	–	475.00	–	3271.00	3012.00	13,084.30
Egbu	–	25.00	–	–	175.00	–	300.00	1078.00	395.00	235.00	1578.00
Ahiara Mbiase	–	25.00	–	–	175.00	–	350.00	560.00	278.00	115.00	1110.00
Amakohia Ikeduru	–	10.00	–	–	175.00	–	100.00	140.00	106.30	35.60	425.00
Kasuwan Shanu[b]	51,500.00	771.50	1.59	10.83	3150.00	406.25	–	–	9307.00	8452.00	55,840.20
Anantigha	–	–	–	–	–	–	50.00	425.00	238.00	187.00	475.00
Nkonibs	–	–	–	–	–	–	50.00	495.00	273.00	222.00	545.00
Iworoko	1442.44	55.00	2745.00	9.00	–	–	–	95.00	869.00	541.00	4346.44
Ikere	886.89	25.00	3832.50	14.83	–	–	–	175.00	987.00	729.00	4934.22
Atikankan	553.56	35.00	4170.00	11.50	–	–	–	95.00	973.00	805.00	4865.06
Iwofe	0.00	–	2520.00	–	–	–	−9.00	0.00	508.00	503.00	2541.00
Rumuodomaya	0.00	–	−26.50	–	12.00	–	−9.00	195.00	34.30	40.70	171.50
Trans-Amadi	0.00	–	0.00	–	22.00	–	300.00	125.00	89.40	57.50	447.00

[a] [13] Kashua Shanu in 2010.

[b] [9] Kasuwan Shanu in 2020. These two are the same abattoir facilities reported by different authors. (-) Not computed due to unreported data.

Source: Authors (2023). [a] [13] Kashua Shanu in 2010; [b] [9] Kasuwan Shanu 2020. These two are the same abattoir facilities reported by different authors. (–) Not computed due to unreported data.

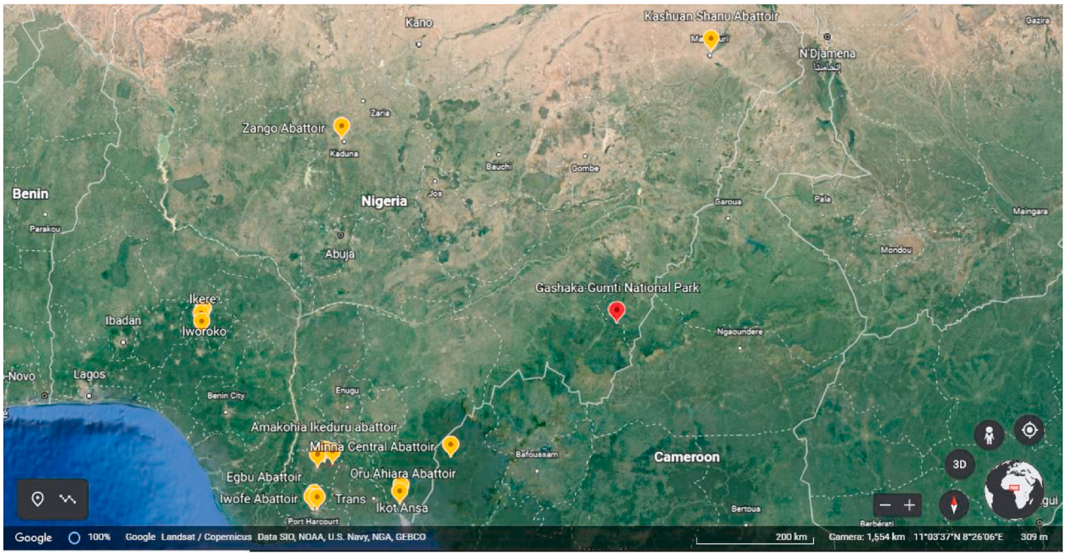

Fig. 1. Map of the study area.

used in many statistics settings. In a meta-analysis, heterogeneity can point to variations across samples, within individual samples, and even within individual experimental outcomes. Incorrect assumptions leading to mistakes in linear models are also covered by heterogeneity [87].

Cochran's Q statistic (without moderators), Higgins and Thompson's I^2statistic, H^2 statistic, heterogeneity variance (τ^2) and SD are primarily used to measure residual heterogeneity in meta-analysis[79].

Cochran's Q statistic, a weighted sum of squares, has often been used to distinguish sampling error from between-study heterogeneity. The Q statistic represents the study's overall variance [88], which is estimated using Equation (6) [79].

$$Q = \sum_{k=1}^{k} w_k \left(\widehat{\theta}_k - \theta\right)^2 \tag{6}$$

where wk, $\widehat{\theta}_k$, and θ are the inverse of the weighted study's variance, the study's observed effect, and summary effects, respectively. According to Borenstein et al. [88], where the only source of variance in a meta-analysis is a within-study error, then the value of the Q statistic would be the degrees of freedom (df). When moderators are incorporated into the model, the test of residual heterogeneity using the Cochran statistic is represented by QE.

The I^2 statistic, which measures between-study heterogeneity, is directly derived from Cochran's Q. It is described as the proportion of effect size variability not due to sampling error. It is calculated using Equation (7) [79] below.

$$I^2 = \frac{Q - df}{Q} \times 100\% \tag{7}$$

where df is the degree of freedom (total number of studies minus one, K-1).

Like the I^2 statistic, the H^2 is derived from Cochran's Q statistic. The H^2 statistic measures the ratio of the observed variation by Q and the expected variance due to sampling error [79] and is calculated using Equation (8) [79] given as follows:

$$H^2 = \frac{Q}{K - 1} \tag{8}$$

The τ^2 measures between-study heterogeneity of the true effect sizes. Like the I^2 and H^2, the τ^2 also depends on the Q statistic. The $\tau^2 = 0$, where $Q < df$. However, when $Q > df$, the τ^2 is calculated using Equation (9) [88].

$$\tau^2 = \frac{Q - df}{C} \tag{9}$$

where C is a scaling factor that is applied to ensure that τ^2 is in the same metric as the variance within studies [88] and C is computed using Equation (10) [88].

$$C = \sum w_i - \frac{\sum w_i^2}{\sum w_i} \tag{10}$$

where w_i is the weighted inverse variance.

There are several other ways of estimating $\tau^{2.}$ However, most are too complex to be performed manually. Interestingly, various estimators are available for heterogeneity variance estimation in meta-analysis in the “meta” package in R. These include DerSimonian-Laird (DL), Paule-Mandel (PM), Restricted Maximum-Likelihood (REML), Maximum-Likelihood (ML), Hunter-Schmidt (HS), Sidik-Jonkman (SJ), Hedges (HE), and Empirical Bayes (EB), which automatically calculate the τ^2 [79].

Every measurement, however, is subject to some level of uncertainty caused by systematic and/or random error. A crucial part of describing scientific research findings recognizes the data’s uncertainty [89]. Sampling, storage conditions, instrument effects, reagent purity, measurement condition, and computational effects, among others, are potential sources of uncertainty in a dataset [90]. According to Sturgiss [89], SD is the most prevalent metric for expressing the spread or uncertainty of data. Hence, this was used for estimating uncertainty in the dataset in this study and is given by Equation (11) [91] below.

$$s = \sqrt{\frac{\sum_{i=1}^{n} (x - \overline{x})^2}{n - 1}} \tag{11}$$

where s is the sample SD, x is the observation, $\overline{x}$ is the mean, and n is the number of samples. The square root of the τ^2 is also an estimated SD of the underlying effects across studies, expressing the uncertainty in this study’s meta-regression model.

4.2.3.3. Fitting the meta-regression model. Fitting a meta-regression model can be assessed by determining how much heterogeneity variance it accounts for [79]. The R_*^2 analog is used to quantify the percentage variance explained by moderators. R_*^2 is computed using Equation (12) or (13) [79].

$$R_*^2 = 1 - \frac{\widehat{\tau}^2_{unexplained}}{\widehat{\tau}^2_{Total}} \tag{12}$$

Or

$$R_*^2 = 1 - \frac{\widehat{\tau}^2_{REM} - \widehat{\tau}^2_{MEM}}{\widehat{\tau}^2_{REM}} \tag{13}$$

where $\widehat{\tau}^2_{REM}$ denotes the between-study heterogeneity in the random-effects model, and $\widehat{\tau}^2_{MEM}$ denotes the residual variance in the mixed-effects meta-regression model.

4.3. Results

4.3.1. Concentration of heavy metals

The heavy metal concentrations reported in abattoir liquid waste from the various literature are presented in Table 6. The authors have also computed descriptive statistics on the different concentrations of the data. The information from the table formed the bases for all other analyses conducted in this study.The uncertainty in the dataset is represented in SD/SE [89].

Across the abattoirs, the mean metal concentrations ranged from 0.07± 0.06 (SD)/0.02 (SE) for Cr to 8.13 ± 25.08 (SD)/7.92(SE) mg/L for Zn, with the metals generally represented. The high uncertainties were due to extremely high Ni, Zn, and Cu levels at the Minna Central abattoir and Fe at the Tudun Wada abattoir. Zn was the most abundant among the heavy metal species in the abattoir liquid wastes, with the highest concentration of 79.5 mg/L, detected at Minna Central abattoir. The following interesting observations were made at the Kashua/Kasuwan Shanu abattoir, the only facility with two different datasets: (i) The concentrations of Cr (0.22 mg/L), Cd (0.74 mg/L), Mn (0.38 mg/L), and Zn (0.25 mg/L) dropped to 0.10, 0.12, 0.13, and 0.18 mg/L [9,13], respectively, after a decade. These correspond to 54.5, 83.8, 65.8, and 28.0% differences; (ii) Only Ni’s concentration increased from 0.41 to 1.5 mg/L, representing 72.7% difference, with Fe maintaining a fairly constant value [0.10 mg/L vs. 0.11 mg/L) over the same timeframe [9,13]; (iii) Kasuwan Shanu abattoir was the only facility in which the Hg profile was investigated over the timeframe, with a concentration of 0.13 mg/L detected in 2020 [9]; (iv) Cu and Pb were not investigated in this abattoir [9]; and (v) Among the metals, Cr had the lowest mean concentration across the 15 abattoirs (Table 6), with the highest detected at Kashua Shanu in 2010 [13]. These results would undoubtedly reflect the magnitudes of E_rs and RIs in a fixed space but varying time at the Kashua/Kasuwan Shanu abattoir.

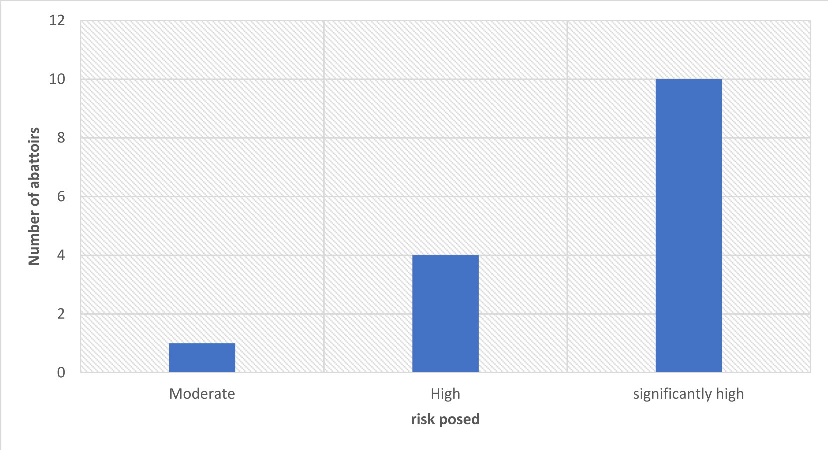

Fig. 2. Bar chart showing risk levels of the 15 studied abattoirs

4.3.2. *RI assessment of heavy metals*

Based on the findings in Table 7, it is observed that of all the abattoirs, Minna Central abattoir liquid waste presented the most significant risk, with Zn being the element presenting the greatest threat with an E_r of 1,391,250.00. Conversely, Cd and Cu in the liquid waste of Rumuodomaya abattoir and Cu in the liquid waste of Iwofe abattoir had negative E_rs. Furthermore, Cr in Iwofe, Rumuodomaya, and Trans-Amadi abattoirs and Cd in Trans-Amadi abattoir had zero E_rs. The zero and negative E_rs suggest that the metals in these abattoir liquid wastes did not appear to have posed any risk since their concentrations (C^i_{0-1}) were lower than their preindustrial background values (C^i_n) (i.e., $C^i_{0-1} < C^i_n$), with the governing equations fully documented by Hakanson [69].

From the risk levels presented in Fig. 2 and Table 7, it is unequivocally concluded that the heavy metals in liquid waste emanating from spatially and operationally independent abattoirs posed moderate to significantly high ecological risks when those studies were conducted. Rumuodomaya abattoir posed a moderate ecological risk, while Trans-Amadi, Nkonibs, Anantigha, and Amakohia Ikeduru abattoirs posed a high risk. All other abattoirs (over 66%) posed a significantly high ecological risk. Over a fixed space but varying time, Kashua Shanu abattoir in 2010 [13] and Kasuwan Shanu abattoir in 2020 [9], both posing significantly high ecological risks, are differentiated with respective mean RIs of 17,287.00 ± 15,472.00 (SE) and 9,307.00 ± 8,452.00 (SE). These values are strongly connected to the differential metal distributions highlighted in subsection 4.3.1. With the ability of heavy metals to bioaccumulate and biomagnify in the biotic systems, their impacts would be disastrous to the ecology in space and time across the study area.

4.3.3. *Meta-regression*

The outcomes of the multiple linear meta-regression are presented in Table 8. Among the τ-estimators (DL, PM, REML, ML, HS, SJ, HE, and EB) in the meta package in R, the Sidik-Jonkman (SJ) provided a more realistic estimate for the effect size than the other estimators, possibly due to its appropriateness for smaller sample size. Hence, this section used it to interpret meta-regression analysis outcomes. The τ^2,which is an estimate of the residual heterogeneity of the true RIs underlying the data, is 0.0032 ± 0.0330 ($\tau^2 \pm SE$). The value of τ is 0.0566, suggesting that the true effect sizes have an estimated SD of 0.0566, which according to Sturgiss [89], depicts the uncertainty in the effect sizes. The value of I^2, the percentage of variability not caused by sampling error or chance, is 4.76%. When I^2 is 0%, variability is explainable by chance alone or sampling error within studies. Therefore, this finding suggests that the low 4.76% of the observed variation in effect sizes could be attributed to sampling error within studies. Still, some underlying factor(s) may act as a potential effect-measure modifier. An I^2 value below 25% is usually deemed as low heterogeneity. Between 25% and 50% is considered moderate, whereas an I^2 value exceeding 50% is deemed high heterogeneity. The I^2 statistic can be used to compare the degree of consistency in the meta-analyses [93]. However, the limitation of I^2 is that it offers a measure of global heterogeneity and, like the Q test, does not reveal information on the source driving this heterogeneity. The H^2 statistic in this study is 1.05, practically indicating the presence of between-study low heterogeneity or complete homogeneity [79]. In contrast to a model where only within variance provides the confidence intervals, H^2 estimates how much uncertainty about the parameter of interest increases due to all sources of variance.

The moderators accounted for an $R^2{}_*$ of 95.73% of the total explanatory capacity of the model. Residual heterogeneity tests the statistical significance of the moderators. The finding suggests that the heterogeneity (QE) not explained by the moderators is not significant ($p > 0.99$), which indicates complete homogeneity, though this statistic has its deficiency. However, the regression coefficients and their corresponding significant p-values for the metal concentrations (Conc.), number of metals analyzed (Num.met), and distance (Dist.) are 0.6624 ($p = 0.0004$), 0.0785 ($p < 0.0001$) and -0.0455 ($p = 0.0108$), respectively. The metal concentrations and distance carried the highest and lowest regression coefficients, respectively. The significantly low p-values imply that the moderators' changes are linked to the response variations.

Table 8
Estimator selection.

Estimator	Model performance				Test for Residual Het.		Test for Moderators		Estimate				SE			
	τ^2	I^2	H^2	R^2	Q	p-value	F	p-value	Intercept	Num. met	Conc	Dist.	Intercept	Num. met	Conc	Dist.
ML (n = 15)	0 (SE = 0.0068)	0	1	100.0	0.3868	1	49.3499	<.0001	−0.0845	0.0793	0.6554	−0.046	0.0353	0.0088	0.1326	0.0148
REML (n = 15)	0 (SE = 0.0225)	0	1	N.A	0.3868	1	49.3499	<.0001	−0.0845	0.0793	0.6554	−0.046	0.0353	0.0088	0.1326	0.0148
PM (n = 15)	0 (SE = 0.0164)	0	1	0.0	0.3868	1	49.3499	<.0001	−0.0845	0.0793	0.6554	−0.046	0.0353	0.0088	0.1326	0.0148
DL (n = 15)	0 (SE = 0.0273)	0	1	0.0	0.3868	1	49.3499	<.0001	−0.0845	0.0793	0.6554	−0.046	0.0353	0.0088	0.1326	0.0148
HE (n = 15)	0 (SE = 0.0348)	0	1	100.0	0.3868	1	49.3499	<.0001	−0.0845	0.0793	0.6554	−0.046	0.0353	0.0088	0.1326	0.0148
EB (n = 15)	0 (SE = 0.0164)	0	1	100.0	0.3868	1	49.3499	<.0001	−0.0845	0.0793	0.6554	−0.046	0.0353	0.0088	0.1326	0.0148
SJ (n = 15)	0.0032 (SE = 0.0330)	4.76	1.05	95.7	0.3868	1	49.3499	<.0001	−0.0828	0.0785	0.6624	−0.0455	0.0349	0.0092	0.1308	0.0149
HS (n = 15)	0 (SE = 0.0120)	0	1	0.0	0.3868	1	49.3499	<.0001	−0.0845	0.0793	0.6554	−0.046	0.0353	0.0088	0.1326	0.0148

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 '' 1. (Num.met = number of metals; Conc. = Concentration of metals; Dist. = Distance of abattoir from GNP; n = number of abattoir); N.A – Not available.

4.4. Discussion

Several human activities pose an enormous risk to the environment and human health, of which the abattoir operations are not exceptional [2,7]. Abattoir operations release several toxic substances into the environment, chief among which are heavy metals [7–9,27,28] such as Cd, Pb, Cr, Ni, Hg, Cu, and Zn, among others. Heavy metals are widely known to present severe damage to all lifeforms upon exposure, sometimes even at minimal concentrations.

Abattoirs are increasingly becoming a major source of worry due to the above-normal heavy metal concentrations reported in several studies and, more importantly, because most of these abattoirs are operating, albeit without the necessary environmental management practices put in place. Several abattoirs discharge liquid wastes into waterways, drainages, and water bodies without the necessary pre-treatment measures. Hence, they directly or indirectly pollute these receiving water bodies [2,62,64], which are the primary water sources for domestic and economic activities for millions of people downstream.These water bodies also serve as habitats for many aquatic organisms.

The findings of this study suggest that liquid waste discharged from almost all of the 15 abattoirs posed high to significantly high risks to the environment, with only one displaying a moderate risk. These imply that the discharged liquid waste would affect human health and aquatic life [2,16,62–64], reducing fish populations in receiving water bodies due to altered habitat conditions such as pH associated with redox reactions of the metals. As a whole, the ecosystem's health and integrity will be compromised. It will also render the receiving water body unsuitable for irrigation purposes, decreasing agricultural productivity, lowering income, aggravating the country's economic woes, and many associated hardships. Complex interactive processes of the metals in the liquid waste may exacerbate the ecological risk due to cumulativeness, synergism, and potentiation, whose consequences are unpredictable and could be alarming.

Several factors account for escalating RIs in abattoir liquid waste. These include (i) Metal concentrations; (ii) Number of metals; (iii) Size of the facilities; (iv) Volume of liquid waste generated per facility; (v) Number of livestock slaughtered/facility/month; (vi) Relative distances of the facilities from a conserved or protected site; (vii) Geomorphology of the river basin; (viii) Rheology of the river basin; (ix) Meteorological conditions and anthropogenic climate change; (x) Hydrology; and (xi) Topography of the catchment area, among others. These factors may be endogeneous or exogeneous to the abattoir settings. However, the three moderators— the number of heavy metals and metal concentrations (endogenous) and distance (exogenous) were identified as good candidates for explaining the RI variation in this study. From the meta-regression analysis, the positive regression coefficients of both the concentration and number of metals mean that the RI linearly and directly depends on these moderators. In contrast, the negative regression coefficient of the distance means that the RI linearly and indirectly depends on distance and this suggests that populations/communities closer to abattoirs or locations of abattoir liquid waste discharge may experience a greater risk. The high model goodness-of-fit R^2_* skill score analog adequately explains the RI variation attributed to the moderators and provides a predictive understanding for future model development for abattoir settings.

The analysis of pooled data [17–19] from different abattoirs from different geographic locations revealed convergence in risk associated with the abattoir liquid waste, evidenced by low residual heterogeneity variance. Conversely, the presence of homogeneity variance, which indicates commonality in operations, irrespective of their geographical locations, with liquid waste posing a severe threat to all lifeforms in the face of global climate change, cannot be understated.

Table 8 (*continued*)

t-value				p-value				Conf. Interval lower boundary				Conf. Interval upper boundary			
Intercept	Num. met	Conc	Dist.	Intercept	Num.met	Conc	Dist.	Intercept	Num. met	Conc	Dist.	Intercept	Num. met	Conc	Dist.
−2.3927	9.0433	4.9427	−3.1136	0.0357*	<.0001 ***	0.0004 ***	0.0099 **	−0.1623	0.0600	0.3635	−0.0785	−0.0068	0.0986	0.9472	−0.0135
−2.3927	9.0433	4.9427	−3.1136	0.0357*	<.0001 ***	0.0004 ***	0.0099 **	−0.1623	0.0600	0.3635	−0.0785	−0.0068	0.0986	0.9472	−0.0135
−2.3927	9.0433	4.9427	−3.1136	0.0357*	<.0001 ***	0.0004 ***	0.0099 **	−0.1623	0.0600	0.3635	−0.0785	−0.0068	0.0986	0.9472	−0.0135
−2.3927	9.0433	4.9427	−3.1136	0.0357*	<.0001 ***	0.0004 ***	0.0099 **	−0.1623	0.0600	0.3635	−0.0785	−0.0068	0.0986	0.9472	−0.0135
−2.3927	9.0433	4.9427	−3.1136	0.0357*	<.0001 ***	0.0004 ***	0.0099 **	−0.1623	0.0600	0.3635	−0.0785	−0.0068	0.0986	0.9472	−0.0135
−2.3927	9.0433	4.9427	−3.1136	0.0357*	<.0001 ***	0.0004 ***	0.0099 **	−0.1623	0.0600	0.3635	−0.0785	−0.0068	0.0986	0.9472	−0.0135
−2.349	8.5138	5.0658	−3.0622	0.0371 *	<.0001 ***	0.0004 ***	0.0108 *	−0.1597	0.0582	0.3746	−0.0782	−0.0059	0.0988	0.9502	−0.0128
−2.3927	9.0433	4.9427	−3.1136	0.0357*	<.0001 ***	0.0004 ***	0.0099 **	−0.1623	0.0600	0.3635	−0.0785	−0.0068	0.0986	0.9472	−0.0135

Signif. codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘’ 1. (Num.met = number of metals; Conc. = Concentration of metals; Dist. = Distance of abattoir from GNP; n = number of abattoir); N.A – Not available.

Although a critical objective of systematic reviews and meta-analyses/meta-regression is to determine the degree to which the findings of several studies are comparable [17–19], this approach has some limitations. For instance, when the sample size is small, several estimators with asymptotic foundations easily tend to be biased [94]. In addition, because meta-regression analyses try to conclude specifics from study-level data, they are prone to the ecological fallacy [94]. Without the capacity to condition the corresponding article-level or individual-level metrics, such as the impact factor of an article or a journal, assessing the impact of aggregate variables can also be challenging. Additionally, it has been observed that non-differential measurement error at the individual level may have the ability to bias group-level effects away from the null. Also, sometimes data on covariates required for the model are not always adequately measured or reported in publications, or some parameters are not investigated. For instance, in this study, data on the quantity of liquid waste generated, the size of the abattoirs, the amount of blood generated, and the number of livestock slaughtered per day, among others, were not reported in the literature used. More discoveries would have been made had we had data for the other moderators mentioned earlier in this study. In this case, multimodel inference in comparative analyses (see, for example, [86] and the references therein) would have provided a more robust, insightful framework for the subject matter. Also, literature reviews are always vulnerable to publication bias, and quantitative methods, in particular, run the risk of data dredging and false positive results [94].

Regardless of the pros and cons of systematic reviews, the evidence-based ecological risk posed to the environment by the cluster of abattoirs in the current study is unquestionable. It calls for actionable policies, plans, programs, and regulations to control this menace [31]. Several jurisdictions and organizations have promulgated regulations (Table 9) to ensure cleaner environments. For instance, the US EPA enacted the Clean Water Act, which forbids the discharge of any pollutant without a permit. The Act includes federally mandated limitations and any additional restrictions needed to safeguard water quality. These regulations have national rules that all enterprises must meet in a specific sector and more stringent permits are required conditions to protect or restore local water quality. The Clean Water Act mandated the agency to establish national “Effluent Limitation Guidelines” to limit harmful emissions from abattoirs and other substantial industrial or municipal effluent sources [95]. While some countries are more environmentally conscious and backed by laws, unfortunately, others do not strictly enforce their laws very often.

Table 9
Regulatory limits for heavy metals (ppm) in liquid waste.

Organization	Trace metals (ppm)								
	Cr	Ni	Cd	Fe	Mn	Zn	Hg	Cu	Pb
WHO	005[a]	0.02[a]	0.03[a]	0.3[d]	5[d]	<1.0[d]	0.001[a]	1[d]	0.01[a]
US EPA	0.05[a]	0.2[a]	0.01[a]	5[b]	–	2[b]	0.00003[a]	0.2[b]	0.006[a]
World Bank	0.1[c]	0.5[a]	0.1[a]	3.5[c]	–	2[c]	0.01[a]	0.5[c]	0.1[a]
Ghana[e]	0.5	0.5	<0.1	–	0.1	5	0.005	2.5	0.1
Kenya[a]	0.05	0.3	0.01	–	–	–	0.005	–	0.01
China[a]	0.5	1.0	0.03	–	–	–	0.005	–	1.0

Signif. codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘’ 1. (Num.met = number of metals; Conc. = Concentration of metals; Dist. = Distance of abattoir from GNP; n = number of abattoir); N.A – Not available; (-) Not provided.
[a] [96], [b] [97], [c] [98], [d] [15], [e] [99].

Apart from these regulatory limits, urban planning should also be the topmost priority for city authorities. Regulations governing the mapping and siting of human settlements and industrial hubs should be strictly enforced and prevent human exposure to toxic abattoir effluents.

5. Conclusions

The meat processing industry uses over 62×10^6 m^3 of water annually, accounting for over 29% of all freshwater in agriculture globally. Abattoir operations generate large quantities of untreated liquid waste, often discharged into the environment. This precarious situation would degrade the already limited global freshwater quality in the long term. Liquid waste has complex characteristics. Heavy metals are vital waste components, and the commonly reported metals include Cu, Zn, Fe, Mn, Cr, Ni, Cd, Hg, and Pb, which have severe ecological implications.

The findings from the meta-analysis/meta-regression performed on the 15 abattoirs have established the following:

(i) Liquid waste from spatially distinct and operationally independent abattoirs demonstrates homogeneity variance and poses a severe ecological risk;
(ii) The concentrations and number of metals in abattoir liquid waste studied have a direct relationship with the RI; and
(iii) The farther the distance of abattoirs from a relatively unpolluted reserve or conserved site, the less the RI, which is an indirect relationship.

The three moderators have provided a predictive understanding of the RIs of the abattoirs. They will be essential for environmental management plan design, city planning, human settlements, and future predictive model development for abattoir liquid waste.

Though several legislations have been enacted to control liquid waste discharge, these are frequently disregarded in several jurisdictions due to laxity/inadequate enforcement or operational limitations. The need for the abattoir industry to be more environmentally conscious is essential in the spirit of ecological restoration, maintenance of ecosystem integrity, wildlife health, and human health. While abattoirs contribute to achieving SDG 1 (End poverty in all its forms everywhere), SDG 2 (End hunger, achieve food security and improved nutrition, and promote sustainable agriculture), and SDG 8 (Promote sustained, inclusive, and sustainable economic growth, full and productive employment and decent work for all), unfortunately, the discharge of untreated abattoir liquid into the environment blatantly violates the very tenets enshrined in SDG 3 (Ensure healthy lives and promote well-being for all and at all ages) and SDG 6 (Ensure availability and sustainable management of water and sanitation for all). The authors dispassionately recognize this ambivalence, which should spark local, national, regional, and global debates focused on SDGs 1, 2, 3, 6, and 8. This proposition would propel relevant stakeholders to initiate actionable policies and prompt interventions to holistically address long-outstanding abattoir liquid waste issues to achieve the SDGs by 2030.

Finally, future studies should focus on the other moderators to deepen our understanding of the interplay of various environmental factors that govern ecological risks associated with abattoir liquid waste.

Author contribution statement

All authors listed have significantly contributed to the development and the writing of this article.

Data availability statement

Secondary data obtained from published scientific articles (see Table 6) were used to calculate the potential ecological risks in the authors' manuscript (see Table 7).

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

References

[1] R. Al-Wasify, A. Mahmoud, S. Ragab, I. Abdelaziz, S. Hamed, A pilot model for slaughterhouse wastewater treatment using Moringa oleifera seed husks, pods and extract followed by aeration, J. Eng. Appl. Sci. 14 (2019) 354–362.
[2] C. Bustillo-Lecompte, M. Mehrvar, in: R. Farooq, Z. Ahmad (Eds.), Slaughterhouse Wastewater: Treatment, Management and Resource Recovery, Physico-Chemical Wastewater Treatment and Resource Recovery, IntechOpen, 2017, https://doi.org/10.5772/65499.
[3] L. Gürel, H. Büyükgüngör, Treatment of slaughterhouse plant wastewater by using a membrane bioreactor, Water Sci. Technol.: J. Int. Assoc. Water Pollut. Res. 64 (1) (2011) 214–219, https://doi.org/10.2166/wst.2011.677.
[4] OECD & FAO of the United Nations, OECD-FAO Agricultural Outlook 2020-2029, OECD Publishing, Paris/FAO, Rome, 2020, https://doi.org/10.1787/1112c23b-en.
[5] M. Henchion, A.P. Moloney, J. Hyland, J. Zimmermann, S. McCarthy, Review: trends for meat, milk and egg consumption for the next decades and the role played by livestock systems in the global production of proteins, Animal 15 (2021), 100287, https://doi.org/10.1016/j.animal.2021.100287.
[6] L. Kirui, J.T. Karugia, Economic Viability of Abattoirs in Arid and Semi-arid Land (ASAL) Counties of Kenya, ILRI, 2019. https://hdl.handle.net/10568/109931.
[7] E.J. Eze, P.O. Phil-Eze, Abattoir effluents and population health risks, J. Environ. Sci., Toxicol. Food Technol. 14 (4) (2020) 49–52, https://doi.org/10.9790/2402-1404014952.

[8] G.S. Mittal, Characterization of the effluent wastewater from abattoirs for land application, Food Rev. Int. 20 (3) (2004) 229–256.
[9] A.I. Mohammed, A.A. Ahmed, T.E. Dauda, Determination of levels of heavy metals and physicochemical parameters in waste water of Kasuwan shanu abattoir, Maiduguri, J. Chem. Lett. 1 (2) (2020) 84–88.
[10] C.N. Eze, P.C. Eze, Effect of abattoir waste on the physicochemical and bacteriological qualities of new-artisan River in Enugu, Nigeria, Niger. J. Technol. 37 (1) (2018) 262–267.
[11] N. Mujere, in: M. Khosrow-Pour, S. Clark, M.E. Jennex, A. Ari-Veikko (Eds.), Water Quality Impacts of Abattoir Activities in Southern Africa, Waste Management: Concepts, Methodologies, Tools, and Applications, IGI Global, 2020, pp. 405–415.
[12] F.O. Owagboriaye, G.A. Dedeke, K.O. Ademolu, O.A. Adebambo, Bioaccumulation of heavy metals in earthworms collected from abattoir soils in Abeokuta, south-western Nigeria, Zool. Soc. Niger. 13 (2015) 36–42.
[13] J.C. Akan, F.I. Abdulrahman, E. Yusuf, Physical and chemical parameters in abattoir wastewater sample, Maiduguri Metropolis, Nigeria, Pac. J. Sci. Technol. 11 (1) (2010) 640–648.
[14] D. Dauda, D. Duro, U.J.J. Ijah, Physicochemical and microbiological qualities of the abattoir wastewater in part of Minna Niger state, Adv. Life Sci. Technol. 51 (2016) 17–25.
[15] A.L. Hassana, L.T. Nuradeen, Evaluation of the efficiency of constructed activated carbon for the treatment of abattoir wastewater, Sci. World J. 16 (2) (2021) 172–178.
[16] M. Singh Sankhla, M. Kumari, M. Nandan, R. Kumar, P. Agrawal, Heavy metals contamination in water and their hazardous effect on human health-a review, Int. J. Curr. Microbiol. Appl. Sci. 5 (2016) 759–766, https://doi.org/10.20546/ijcmas.2016.510.082.
[17] E. Ahn, H. Kang, Introduction to systematic review and meta-analysis, Kor. J. Anesthesiol. 71 (2) (2018) 103–112, https://doi.org/10.4097/kjae.2018.71.2.103.
[18] M.W. Russo, How to review a meta-analysis, Gastroenterol. Hepatol. 3 (8) (2007) 637–642.
[19] G.M. Tawfik, K.A.S. Dila, M.Y.F. Mohamed, D.N.H. Tam, N.D. Kien, A.M. Ahmed, N.T. Huy, A step-by-step guide for conducting a systematic review and meta-analysis with simulation data, Trop. Med. Health 47 (1) (2019) 1–9.
[20] N. Carter, D. Bryant-Lukosius, A. DiCenso, J. Blythe, A.J. Neville, The use of triangulation in qualitative research, Oncol. Nurs. Forum 41 (5) (2014) 545–547, https://doi.org/10.1188/14.ONF.545-547.
[21] L.A. Guion, D.C. Diehl, D. McDonald, Triangulation: establishing the validity of qualitative studies: FCS6014/FY394, Rev. 8/2011, Edis 2011 (8) (2011) 3.
[22] S.T. Ubwa, G.H. Atoo, J.O. Offem, J. Abah, K. Asemave, An assessment of surface water pollution status around Gboko abattoir, Afr. J. Pure Appl. Chem. 7 (3) (2013) 131–138.
[23] V. Mozhiarasi, T.S. Natarajan, Slaughterhouse and poultry wastes: management practices, feedstocks for renewable energy production, and recovery of value added products, Biomass Convers. Biorefinery (2022) 1–24, https://doi.org/10.1007/s13399-022-02352-0.
[24] W.C. Mamhobu-Amadi, B.S. Kinigoma, Y.L.O. Momoh, A.A. Oji, Abattoir operations and waste Management Options: a review, Int. J. Adv. Eng. Res. Sci. 6 (12) (2019) 226–231.
[25] J.W. Savell, S.L. Mueller, B.E. Baird, The chilling of carcasses, Meat Sci. 70 (3) (2005) 449–459, https://doi.org/10.1016/j.meatsci.2004.06.027.
[26] J.D. Stopforth, J.N. Sofos, in: J.N. Sofos (Ed.), Carcass Chilling, Improving the Safety of Fresh Meat, Woodhead Publishing, 2005, pp. 364–387, https://doi.org/10.1533/9781845691028.2.364.
[27] D.I. Massé, L. Masse, Characterization of wastewater from hog slaughterhouses in Eastern Canada and evaluation of their in-plant wastewater treatment systems, Can. Agric. Eng. 42 (3) (2000) 139–146.
[28] O. Osibanjo, G.U. Adie, Impact of effluent from Bodija abattoir on the physicochemical parameters of Oshunkaye stream in Ibadan City, Nigeria, Afr. J. Biotechnol. 6 (15) (2007), https://doi.org/10.5897/AJB2007.000-2266.
[29] E.A. Awafo, J. Amenorfe, Techno-economic studies of an industrial biogas plant to be implemented at Kumasi Abattoir in Ghana, Sci. Afr. 11 (2021), e00712, https://doi.org/10.1016/j.sciaf.2021.e00712.
[30] A. Mulu, T. Ayenew, Characterization of abattoir wastewater and evaluation of the effectiveness of the wastewater treatment systems in Luna and Kera abattoirs in Central Ethiopia, Int. J. Sci. Eng. Res. 6 (4) (2015) 15.
[31] C.F. Bustillo-Lecompte, M. Mehrvar, Slaughterhouse wastewater characteristics, treatment, and management in the meat processing industry: a review on trends and advances, J. Environ. Manag. 161 (2015) 287–302, https://doi.org/10.1016/j.jenvman.2015.07.008.
[32] Z. Yousefi, M. Behbodi, R.A. Mohammadpour, Slaughterhouse wastewater treatment by combined anaerobic baffled reactor and anaerobic filter: study of OLR and HRT optimization in ABR/AF reactors, Environ. Eng Manag. J. 5 (2018) 137–142, https://doi.org/10.15171/EHEM.2018.20.
[33] R. Del Pozo, V. Diez, Integrated anaerobic–aerobic fixed-film reactor for slaughterhouse wastewater treatment, Water Res. 39 (6) (2005) 1114–1122, https://doi.org/10.1016/j.watres.2005.01.013.
[34] K. Acevedo-Whitehouse, L.J. Amanda, A.L.J. Duffus, Effects of environmental change on wildlife health, Philos. Trans. R. Soc. B 364 (2009) 3429–3438, https://doi.org/10.1098/rstb.2009.0128.
[35] H. Shi, M. Zeng, H. Peng, C. Huang, H. Sun, Q. Hou, P. Pi, Health risk assessment of PTEs in groundwater of Hainan Island using the Monte Carlo simulation coupled with the APCS/MLR model, Int. J. Environ. Res. Publ. Health 19 (13) (2022) 7827.
[36] A. Royer, T. Sharman, Copper Toxicity, StatPearls Publishing, 2022. http://www.ncbi.nlm.nih.gov/books/NBK557456/.
[37] National Institutes of Health (NIH) Office of Dietary Supplements (ODS), Fact Sheets for Health Professionals: Copper, 2021. https://ods.od.nih.gov/factsheets/Copper-HealthProfessional/.
[38] E. Atangana, Production, disposal, and efficient technique used in the separation of heavy metals from red meat abattoir wastewater, Environ. Sci. Pollut. Control Ser. 27 (9) (2020) 9424–9434, https://doi.org/10.1007/s11356-019-06850-z.
[39] J.Y. Magaji, C.D. Chup, The effects of abattoir waste on water quality in Gwagwalada-Abuja, Nigeria, Ethiop. J. Environ. Stud. Manag. 5 (4) (2012) 542–549.
[40] P.T. Bhattacharya, S.R. Misra, M. Hussain, Nutritional aspects of essential trace elements in oral health and disease: an extensive review, Sci. Tech. Rep. 2016 (2016), 5464373, https://doi.org/10.1155/2016/5464373.
[41] L.M. Plum, L. Rink, H. Haase, The essential toxin: impact of zinc on human health, Int. J. Environ. Res. Publ. Health 7 (4) (2010) 1342–1365, https://doi.org/10.3390/ijerph7041342.
[42] V. Kumar, P.K. Bharti, M. Talwar, A.K. Tyagi, P. Kumar, Studies on high iron content in water resources of Moradabad district (UP), India, Water Sci. 31 (1) (2017) 44–51, https://doi.org/10.1016/j.wsj.2017.02.003.
[43] EFSA FEEDAP, Safety and efficacy of iron compounds (E1) as feed additives for all animal species: ferrous carbonate; ferric chloride, hexahydrate; ferrous fumarate; ferrous sulphate, heptahydrate; ferrous sulphate, monohydrate; ferrous chelate of amino acids, hydrate; ferrous chelate of glycine, hydrate, based on a dossier submitted by FEFANA asbl, EFSA J. 14 (2) (2016) 4396, https://doi.org/10.2903/j.efsa.2016.4396.
[44] T.G. Kornberg, T.A. Stueckle, J.M. Antonini, Y. Rojanasakul, V. Castranova, Y. Yang, L.W. Rojanasakul, Potential toxicity and underlying mechanisms associated with pulmonary exposure to iron oxide nanoparticles: conflicting literature and unclear risk, Nanomaterials 7 (10) (2017) 307, https://doi.org/10.3390/nano7100307.
[45] A.W. Dobson, K.M. Erikson, M. Aschner, Manganese neurotoxicity, Ann. N. Y. Acad. Sci. 1012 (1) (2004) 115–128, https://doi.org/10.1196/annals.1306.009.
[46] M. Williams, G.D. Todd, N. Roney, J. Crawford, C. Coles, P.R. McClure, J.D. Garey, K. Zaccaria, M. Citra, Toxicological Profile of Manganese, Agency for Toxic Substances and Disease Registry (US), 2012. https://www.ncbi.nlm.nih.gov/books/NBK158868/.
[47] B. Brennan, B. Gunes, M.R. Jacobs, J. Lawler, F. Regan, Potential viable products identified from characterisation of agricultural slaughterhouse rendering wastewater, Water 13 (3) (2021) 352.
[48] S. Prasad, K.K. Yadav, S. Kumar, N. Gupta, M.M.S. Cabral-Pinto, S. Rezania, N. Radwan, J. Alam, Chromium contamination and effect on environmental health and its remediation: a sustainable approaches, J. Environ. Manag. 285 (2021), 112174, https://doi.org/10.1016/j.jenvman.2021.112174.
[49] O.O. Elemile, O.D. Raphael, D.O. Omole, O.E. Oluwatuyi, E.O. Ajayi, O. Umukoro, M.G. Elemile, Assessment of the impact of abattoir activities on the physicochemical properties of soils within a residential area of Omu-Aran, Nigeria, IOP Conf. Ser. Mater. Sci. Eng. 640 (1) (2019), 012083, https://doi.org/10.9734/mrji/2019/v28i630147.

[50] M. Tumolo, V. Ancona, D. De Paola, D. Losacco, C. Campanale, C. Massarelli, V.F. Uricchio, Chromium pollution in European water, sources, health risk, and remediation strategies: an overview, Int. J. Environ. Res. Publ. Health 17 (15) (2020) 5438, https://doi.org/10.3390/ijerph17155438.
[51] G. Genchi, M.S. Sinicropi, G. Lauria, A. Carocci, A. Catalano, The effects of cadmium toxicity, Int. J. Environ. Res. Publ. Health 17 (11) (2020) 3782, https://doi.org/10.3390/ijerph17113782.
[52] WHO, Preventing Disease through Healthy Environments: Exposure to Cadmium: a Major Public Health Concern, World Health Organization (WHO), Geneva, Switzerland, 2019, pp. 3–6.
[53] M. Sakakibara, K. Sera, I.A. Kurniawan, Mercury contamination of cattle in artisanal and small-scale gold mining in Bombana, Southeast Sulawesi, Indonesia, Geosciences 7 (4) (2017) 133, https://doi.org/10.3390/geosciences7040133. MDPI AG. Retrieved from.
[54] E. Suess, M. Berg, S. Bouchet, L. Cayo, S.J. Hug, R. Kaegi, A. Voegelin, L.H.E. Winkel, E. Tessier, D. Amouroux, A.M. Buser, Mercury loads and fluxes from wastewater: a nationwide survey in Switzerland, Water Res. 175 (2020), 115708, https://doi.org/10.1016/j.watres.2020.115708.
[55] A.L. Wani, A. Ara, J.A. Usmani, Lead toxicity: a review, Interdiscipl. Toxicol. 8 (2) (2015) 55–64, https://doi.org/10.1515/intox-2015-0009.
[56] C.O. Egesi, V. Ezebuiro, A.C. Ekeleme, C.E. Obiukwu, Compliance monitoring of microbiological and physicochemical parameters of abattoirs' effluents discharged into water bodies in Owerri, Nigeria, Microbiol. Res. J. Int. 28 (6) (2019) 1–16, https://doi.org/10.9734/mrji/2019/v28i630147.
[57] E.O. Obanijesu, J.O. Olajide, in: E.K. Yanful (Ed.), Trace Metal Pollution Study on Cassava Flour's Roadside Drying Technique in Nigeria, Appropriate Technologies for Environmental Protection in the Developing World, Springer, Dordrecht, 2009, pp. 333–339, https://doi.org/10.1007/978-1-4020-9139-1_32.
[58] S.A. Kiyawa, Lead (Pb) levels in soils and plants growing near heavy machinery activities in Bagwai, Kano–Nigeria, Int. J. Chem., Mater. Environ. Res. 2 (1) (2015) 26–31.
[59] Institute of Medicine (US) Panel on Micronutrients, Dietary Reference Intakes for Vitamin A, Vitamin K, Arsenic, Boron, Chromium, Copper, Iodine, Iron, Manganese, Molybdenum, Nickel, Silicon, Vanadium, and Zinc, National Academies Press (US), 2001, https://doi.org/10.17226/10026.
[60] A.K.M.A. Ullah, M.A. Maksud, S.R. Khan, L.N. Lutfa, S.B. Quraishi, Dietary intake of heavy metals from eight highly consumed species of cultured fish and possible human health risk implications in Bangladesh, Toxicol Rep 4 (2017) 574–579, https://doi.org/10.1016/j.toxrep.2017.10.002.
[61] K.M. Rice, E.M. Walker, M. Wu, C. Gillette, E.R. Blough, Environmental mercury and its toxic effects, J. Prevent. Med. Publ. Health 47 (2) (2014) 74–83, https://doi.org/10.3961/jpmph.2014.47.2.74.
[62] A. Abdullahi, N. Kadarman, A. Hassan, I.S. Madobi, Negative impact of abattoir activities and management in residential neighbourhoods in Kuala terengganu, Malaysia, Int. J. Publ. Health Sci. (IJPHS) 4 (2) (2015) 124–130.
[63] A.A. Adegbola, A.O. Adewoye, O. Abosede, On investigating pollution of groundwater from Atenda Abattoir wastes, Ogbomoso, Nigeria, Int. J. Eng. Technol. 2 (9) (2012) 1569–1585.
[64] S.S. Murugan, R. Karuppasamy, K. Poongodi, S. Puvaneswari, Bioaccumulation pattern of zinc in freshwater fish Channa punctatus (Bloch.) after chronic exposure, Turk. J. Fish. Aquat. Sci. 8 (1) (2008) 55–59.
[65] EPA Victoria, Guidelines for Risk Assessment of Wastewater Discharges to Waterways, vol. 1287, EPA Publication, 2009, pp. 1–16. www.epa.vic.gov.au.
[66] S. Pongpiachan, A. Iijima, J. Cao, Hazard quotients, hazard Indexes, and cancer risks of toxic metals in PM10 during Firework displays, Atmosphere 9 (4) (2018) 144, https://doi.org/10.3390/atmos9040144.
[67] H. Liang, J. Gong, K. Zhou, L. Deng, J. Chen, L. Guo, M. Jiang, J. Lin, H. Tang, X. Liu, Removal efficiencies and risk assessment of endocrine-disrupting chemicals at two wastewater treatment plants in South China, Ecotoxicol. Environ. Saf. 225 (2021), 112758, https://doi.org/10.1016/j.ecoenv.2021.112758.
[68] A.D. Lemly, Evaluation of the hazard quotient method for risk assessment of selenium, Ecotoxicol. Environ. Saf. 35 (2) (1996) 156–162, https://doi.org/10.1006/eesa.1996.0095.
[69] L. Hakanson, An ecological risk index for aquatic pollution control. A sedimentological approach, Water Res. 14 (8) (1980) 975–1001, https://doi.org/10.1016/0043-1354(80)90143-8.
[70] Z. Kang, S. Wang, J. Qin, R. Wu, H. Li, Pollution characteristics and ecological risk assessment of heavy metals in paddy fields of Fujian province, China, Sci. Rep. 10 (1) (2020), 12244, https://doi.org/10.1038/s41598-020-69165-x.
[71] Z. Banu, M.S.A. Chowdhury, M.D. Hossain, K.I. Nakagami, Contamination and ecological risk assessment of heavy metal in the sediment of Turag River, Bangladesh: an index analysis approach, J. Water Resour. Protect. 5 (2) (2013) 239–248, https://doi.org/10.4236/jwarp.2013.52024.
[72] N.F. Soliman, S.M. Nasr, M.A. Okbah, Potential ecological risk of heavy metals in sediments from the Mediterranean coast, Egypt, J. Environ. Health Sci. Eng. 13 (2015) 70, https://doi.org/10.1186/s40201-015-0223-x.
[73] J. Liao, X. Cui, H. Feng, S. Yan, Environmental background values and ecological risk assessment of heavy metals in watershed sediments: a comparison of assessment methods, Water 14 (1) (2022) 51, https://doi.org/10.3390/w14010051.
[74] T. Ntakirutimana, G. Du, J. Guo, X. Gao, L. Huang, Pollution and potential ecological risk assessment of heavy metals in a lake, Pol. J. Environ. Stud. 22 (4) (2013) 1129–1134.
[75] L. Yu, F. Zhang, K. Zang, L. He, F. Wan, H. Liu, X. Zhang, Z. Shi, Potential ecological risk assessment of heavy metals in cultivated land based on soil geochemical zoning: Yishui County, North China Case Study, Water 13 (23) (2021) 3322, https://doi.org/10.3390/w13233322.
[76] A. Kabata-Pendias, H. Pendias, Trace Elements in Soils and Plants, third ed., CRC Press, Boca Raton, 2001.
[77] J.B. Kowalska, R. Mazurek, M. Gąsiorek, T. Zaleski, Pollution indices as useful tools for the comprehensive evaluation of the degree of soil contamination–A review, Environ. Geochem. Health 40 (6) (2018) 2395–2420.
[78] G.A. Ebong, E.S. Ettesam, E.U. Dan, Impact of abattoir wastes on trace metal accumulation, speciation, and human health–related problems in soils within Southern Nigeria, Air Soil. Water Res. 13 (2020) 1–14, https://doi.org/10.1177/1178622119898430.
[79] M. Harrer, P. Cuijpers, T.A. Furukawa, D.D. Ebert, Doing Meta-Analysis with R: A Hands-On Guide, Chapman and Hall/CRC, 2021.
[80] T.C. Azuonwu, D.N. Ogbonna, J. Onwuteaka, Physicochemistry and heavy metal characteristics of waste products from abattoir activities in Port Harcourt, Nigeria, Asian J. Adv. Res. Rep. (2019) 1–12, https://doi.org/10.9734/ajarr/2019/v7i430183.
[81] T.M. Ogunlade, B.R. Babaniyi, F.J. Afolabi, G.G. Babaniyi, Physicochemical, heavy metals and microbiological assessment of wastewater in selected abattoirs in Ekiti State, Nigeria, J. Environ. Treat. Tech. 9 (4) (2021) 788–795.
[82] R.B. Agbor, S.P. Antai, Physicochemical and microbial properties of water samples around abattoirs in calabar, Int. J. Sci. Eng. Res. 10 (6) (2019) 1317–1335.
[83] BirdLife International, Important Bird Areas Factsheet: Gashaka-Gumti National Park, 2023. Downloaded from, http://www.birdlife.org. on 06/02/2023.
[84] J.P.T. Higgins, S.G. Thompson, Controlling the risk of spurious findings from meta-regression, Stat. Med. 23 (11) (2004) 1663–1682, https://doi.org/10.1002/sim.1752.
[85] R Core Team, R: A Language and Environment for Statistical Computing, R Foundation for Statistical Computing, Vienna, Austria, 2022. https://www.R-project.org/.
[86] I.K. Tetteh, E. Awuah, E. Frempong, An empirical perspective on environmental antecedents: Part II-stochastic AR (1) modeling for retrospective prediction of the environmental quality of three riparian communities associated with two dams in Kumasi, Ghana, Environ. Res. J. 6 (2012) 37–51.
[87] J. Frost, Heterogeneity in Data and Samples for Statistics, Statistics By Jim, 2021. https://statisticsbyjim.com/basics/heterogeneity/.
[88] M. Borenstein, L. Hedges, H. Rothstein, Meta-Analysis: Fixed Effect vs. Random Effects, Meta-analysis.com, 2007, pp. 1–30.
[89] J. Sturgiss, Uncertainty, error and confidence in data, J. Prof. Learn. 9 (2020).
[90] S.L. Ellison, A. Williams, Quantifying Uncertainty in Analytical Measurement, 2012.
[91] D.K. Lee, J. In, S. Lee, Standard deviation and standard error of the mean, Kor. J. Anesthesiol. 68 (3) (2015) 220–223, https://doi.org/10.4097/kjae.2015.68.3.220.
[92] OriginPro, Version 2021. OriginLab Corporation, Northampton, 2021.
[93] J.P.A. Ioannidis, N.A. Patsopoulos, E. Evangelou, Uncertainty in heterogeneity estimates in meta-analyses, BMJ Br. Med. J. 335 (7626) (2007) 914–916, https://doi.org/10.1136/bmj.39343.408449.80.
[94] S.G. Thompson, J.P.T. Higgins, How should meta-regression analyses be undertaken and interpreted? Stat. Med. 21 (11) (2002) 1559–1573, https://doi.org/10.1002/sim.1187.

[95] K. Burkhart, C. Bernhardt, T. Pelton, E. Schaeffer, A. Phillips, Water Pollution from Slaughterhouses: Three Quarters of US Meat Processing Plants that Discharge into Waterways Violated Their Permits, 2016–2018, Environmental Integrity Project, Washington, DC, USA, 2018.
[96] G.K. Kinuthia, V. Ngure, D. Beti, R. Lugalia, A. Wangila, L. Kamau, Levels of heavy metals in wastewater and soil samples from open drainage channels in Nairobi, Kenya: community health implication, Sci. Rep. 10 (1) (2020) 8434, https://doi.org/10.1038/s41598-020-65359-5.
[97] M.A. Agoro, A.O. Adeniji, M.A. Adefisoye, O.O. Okoh, Heavy metals in wastewater and sewage sludge from selected municipal treatment plants in Eastern Cape Province, South Africa, Water 12 (10) (2020) 2746.
[98] World Bank Group, Pollution Prevention and Abatement Handbook. Washington, DC, 1998, https://doi.org/10.1596/0-8213-3638-X.
[99] E. Owusu-Ansah, A. Sampson, S.K. Amponsah, R. Abaidoo, T. Hald, Performance, compliance and reliability of waste stabilization pond: effluent discharge quality and environmental protection agency standards in Ghana, Res. J. Appl. Sci. Eng. Technol. 10 (2015) 1293–1302, https://doi.org/10.19026/rjaset.10.1825.