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WASTE LEMON PEEL AS A CIRCULAR SOLUTION FOR THE REMEDIATION OF LEAD-CONTAMINATED SLUDGE FOR LAND APPLICATION

[*1]Duru Chinonye, [1,2] Ibrahim Fatima Badiru and [1]Dandajeh Aliyu Adamu

[1]Department of Water Resources and Environmental Engineering, Ahmadu Bello University Zaria
[2]African Centre of Excellence on New Pedagogies in Engineering Education, Ahmadu Bello University Zaria

*Corresponding authors' email: chinonyeduru0@gmail.com Phone: +2349035755209

ABSTRACT

Lead-contaminated sludge is a major environmental concern, as land application of this material can contaminate surfaces with toxic heavy metals. To address this, a novel approach to utilizing waste lemon peel (WLP) for the remediation of lead-contaminated sludge for land application with the circular economy in perspective is presented. The WLP was collected from local producers and characterized using Fourier transform infrared (FTIR) spectroscopy to determine the functional groups present. The hydroxyl, carboxyl, ether, and amide groups are the main functional groups in the sample and they have been identified as potential sites responsible for binding heavy metal ions to the biomass.

The sludge samples were collected from the Ahmadu Bello University Water treatment plant and analyzed for contamination. The effects of WLP on the lead sorption were investigated using batch experiments. The results indicated that lead sorption onto the WLP was significantly as high as 90.5%. The WLP was found to effectively reduce the lead from the contaminated sludge. This study aimed to identify the capability of WLP as a low-cost and sustainable material for the remediation of lead-contaminated sludge for land application, indicating the potential for waste materials to be utilized in the circular economy. The Material Circularity Indicator of 0.835 indicated a highly circular system.

Keywords: Circular economy, waste lemon peel, Lead contamination, sludge, Land Remediation

INTRODUCTION

The world is facing a growing challenge of managing waste and reducing its environmental impact, (Roland, 2018). The majority of waste is disposed of in landfills or incinerators, leading to environmental pollution, greenhouse gas emissions, and depletion of natural resources.

To tackle this issue, one can consider adopting a circular economy approach that prioritizes the elimination of waste and maximizes the use of materials. The principles of design for durability, reuse, repair, refurbishment, remanufacturing, recycling, and recovery form the foundation of a circular economy (Ciriminna *et al*, 2020). The application of these principles across different sectors and industries can enable a circular economy to generate value from waste materials and minimize the need for extracting new resources. The shift from a linear to a circular economy is currently a popular topic of discussion among both academic circles and governments (Upadhayay *et al.*, 2019). In a linear economy, natural resources are extracted and converted into finished goods, which are then consumed and discarded as waste. Given that the world has a finite number of resources, a linear economy cannot be considered a sustainable long-term strategy. Conversely, a circular economy is a model that is designed to be restorative and regenerative. (EM Foundation, 2015). The features of a circular economy include low pollutant emission, low energy consumption, waste elimination, and increased efficiency (Murray *et al.*, 2017). The circular economy approach distinguishes between two types of cycles: technical and biological. In the technical cycle, materials, products, and components are kept in the market for as long as possible through repair, reuse, remanufacture, and recycling. In the biological cycle, non-toxic materials can be directly reintroduced into the biosphere. The importance of restoration in this approach cannot be overstated, as it enables it to not only prevent damage but also actively repair any previous harm (Murray *et al.*, 2017).

The potential to recycle valuable components such as organic matter and plant nutrients has led to a growing interest in spreading sludge on agricultural land. (Xing *et al.*, 2011). This is however limited by the presence of potentially hazardous constituents which include heavy metals present in sludge (Bettiol and Ghini, 2011). Reports have shown that this exercise inadvertently leads to the accumulation of pollutants in soils and can contaminate groundwater by leaching through the soil profile under certain conditions (Li *et al.*, 2011).

The term heavy metal refers to any naturally occurring metallic chemical element that has a relatively high density, at least five times greater than that of water. At low concentrations, heavy metals can be toxic or poisonous. (Paksamut and Boonsong, 2018). Heavy metals are naturally occurring in the earth and cannot be degraded or destroyed. Although these elements are lacking in abundance they are not lacking in significance. Mercury and lead, among other heavy metals, are commonly used in technology despite their toxicity, which can cause harm even in small amounts. The concern for heavy metals stems from their non-biodegradability, toxicity, and persistence in the environment (Dutta, 2002). Heavy metals have been classified among the major causes of environmental pollution and have been studied to cause severe illness and sudden death in human beings for many centuries. Zamfara lead poisoning is the worst recorded heavy metals incidence in the Nigerian records that claimed the lives of over 500 children within seven months in 2010 (Galadima *et al.*, 2011).

Due to the awareness of the negative impacts of high concentrations of heavy metals on the environment, stringent guidelines and verifications have been designed to limit the application of sludge to agricultural soils (Hudcova *et al.*, 2019). To achieve a more sustainable sludge utilization, it is essential to extract heavy metals from the sludge before application. Sludge could be regarded as an organic soil conditioner when the heavy metal levels in it are reduced. With the aforementioned problems in mind, the search is on for environmentally friendly extractants, which have the additional advantages of being readily available, non-toxic, and relatively low in cost for efficient heavy metal removal (Xin *et al*.,2006). Several washing agents, including acids, surfactants, redox agents, and chelating agents, have demonstrated their efficacy in the remediation of soil contaminated with heavy metals (Dermont et al., 2008). However, many of these agents have drawbacks, such as high cost and soil structure disruption. For instance, Dermont et al. suggested that strong acids may damage the soil's fundamental properties and structure, affecting soil fertility and microbial activity.

Besides environmental and social aspects, economic issues must also be considered when choosing the most appropriate treatment and management methods. The existing solid waste management techniques are increasingly being replaced with discussions on the application of circular economy principles in solid waste handling. In recent years, the circular economy concept has received increasing attention worldwide due to the recognition of the fact that the security of the supply of resources and resource efficiency are crucial for the prosperity of economies and companies. For this reason, it has become necessary to change the linear model of the material flow to a closed loop to capture an additional value from products and materials, decrease the amount of waste going to landfills, and reduce the risk presented by the material price volatility and changing costs of the material supply (Janik 2017). Hence, research is required to examine the challenges and opportunities of implementing the principle at the industrial levels of a typical developing economy such as Nigeria.

One example of a sector that can benefit from a circular economy is the wastewater treatment industry. Wastewater treatment plants generate large amounts of sludge that contain organic matter, metals, pathogens, and other pollutants. This sludge can pose serious risks to human health and the environment if not properly disposed of or treated. Therefore, finding alternative ways to use sludge as a valuable resource is crucial for achieving sustainability goals.

One potential alternative is to use sludge as a fertilizer for land application. Land application refers to spreading sludge on agricultural fields or gardens to improve soil quality and crop yield. However, not all types of sludge are suitable for land application. Some sludges may contain toxic substances or pathogens that can contaminate crops or soil. Moreover, some sludges may have low nutrient content or high moisture content that can affect soil fertility or water retention.

To overcome these challenges, researchers have explored various methods of remediating lead-contaminated sludge before using it for land application. Lead is a heavy metal that can accumulate in plants and animals through the food chain. Exposure to lead can cause adverse effects on human health such as neurological disorders, kidney damage, reproductive problems, and cancer, National Health and Medical Research Council. (2015). Therefore, it is important to remove lead from sludge before applying it to crops or gardens.

One method of remediating lead-contaminated sludge is using waste lemon peel (WLP). WLP is a by-product of citrus fruit processing that contains organic matter and bioactive compounds such as citric acid, flavonoids (cardioprotective, chemopreventive, and neuroprotective effects), vitamin C (antioxidant properties), and citrate (lead chelation ability), (Suri et al, 2021). This study aimed to evaluate the feasibility and effectiveness of using WLP for remediating lead-contaminated sludge for land application. The study hypothesized that WLP could reduce the concentration of lead in sludge by adsorption or precipitation mechanisms. The study also hypothesized that WLP could enhance the physical properties (such as pH)), and biological properties (such as microbial activity).

MATERIALS AND METHOD

Sludge preparation

The sludge was allowed to settle for 24 hours and excess water was decanted. The wet sludge was then centrifuged in 45ml tubes at 2000rpm to further reduce moisture content after which it was placed in a crucible and oven dried for one hour at 100ºC.

The dried sludge was pounded with a laboratory mortar and sieved with a 212-micron sieve (Mesh 70).

Sludge Characterization

The sludge sample was analyzed for its physical and chemical properties to determine its feasibility to be used as an alternative to commercial fertilizer. Properties analyzed include pH, total nitrogen, available phosphate, total potassium, and lead content.

Preparation of Lemon Peel Extract

The fresh lemon peels were washed thoroughly with tap water to get rid of dirt and then rinsed with distilled water to remove impurities. It was spread out on a tray to air dry and get rid of dripping water and then transferred into an oven. The peels were oven dried at 50ºC for 12 hours and then heated at 100ºC for 2 hours. The dried peels were then ground in an 8-inch milling machine and sieved with a 212-micron sieve (Mesh 70).

The sieved particles were added into three separate beakers in different masses of 20 g, 60 g, and 100g and were filled with 1000 mL of distilled water. The mixtures were transferred into 1-liter plastic bottles, placed on a mechanical shaker, and shaken for 24 hours at a constant speed. Subsequently, the suspensions were filtered with a mesh sieve to remove the residue, the extracts were further centrifuged at 2000 rpm for 10 minutes until a homogenous mixture was obtained and decanted.

By adding different masses of the lemon peel powder, solutions with different concentrations were prepared for the experiment. Their concentrations are expressed as the ratio of the initial mass of lemon peel powder and the volume of the distilled water.

$$\text{Extract Concentration} = \frac{\text{Initial mass of lemon peel powder(g)}}{\text{Volume of distilled water(L)}} \tag{1}$$

Therefore, lemon peel extracts of 20g/L, 60g/L, and 100g/L were prepared.

The extracts were continually stored in a fridge at 4ºC for subsequent experiments.

Characterization of lemon peel extract

The lemon peel extract was analyzed for its physical and chemical properties to determine its possible effects on the existing properties of the sludge. Properties analyzed include pH, total nitrogen, available phosphate, total potassium, and lead content.

FTIR Analysis of Lemon Peel

To identify the participant functional groups, present in the extract, the original lemon peel powder and residual lemon peel powder after extraction were characterized using a Fourier transform infrared spectroscopy (FTIR) spectrophotometer. The IR spectrum of the lemon peel was recorded using FT-IR8400S within the range of 4000cm^{-1} and 600cm^{-1} with KBr (potassium bromide) disc as reference.

Material Circularity Indicator

The Material Circularity Indicator (MCI), developed by the Ellen MacArthur Foundation and Granta Design, is an indicator that may be applied to assess both product and company circularity. The Material Circularity Indicator of a product (MCI$_P$) measures the extent to which the linear flow has been minimized and the restorative flow has been maximized for the product component. It also measures how long and how intensively a product is used compared to a similar industry-average product. (Ellen MacArthur Foundation 2017). In this respect, the product is assigned a score between 0 and 1 with 0 being a completely linear flow and 1 being a completely circular flow. The MCI$_P$ is constructed by computing the following variables:

i. The total amount of virgin feedstock material (V) used in the product manufacturing.
ii. The total amount of unrecoverable waste (W) attributed to the product, which takes account of the amount of unrecoverable waste or material going to the landfill, the amount of unrecoverable waste generated in the process of recycling a relevant part or material, and the amount of unrecoverable waste generated to produce any recycled content used as feedstock.
iii. The Linear Flow Index (LFI), which measures the proportion of materials flowing in a linear fashion, sourced from virgin materials and ending up as unrecoverable waste; the LFI index takes a value between 1 and 0, where 1 is a completely linear flow and 0 a completely restorative flow,
iv. The utility factor (X), takes account of the length of the phase of the product use (lifetime) and the intensity of the product use (functional unit).

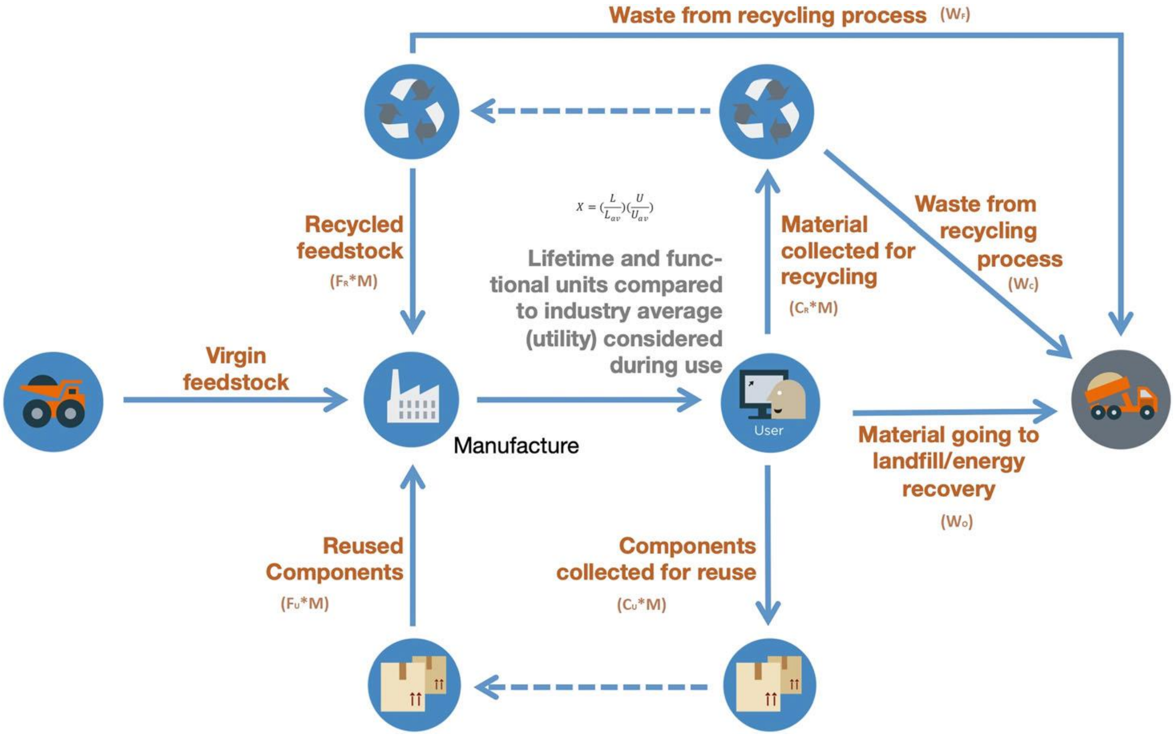

Figure 1: Calculation of MCI (source: EM Foundation 2015)

To compute the MCI$_P$, the following formulae defining relevant variables need to be applied (Ellen MacArthur Foundation 2020)

i. The amount of the virgin feedstock material:

$$V = M \times (1 - F_R - F_U) \qquad (2)$$

where: M is the mass of the material, F$_R$ represents the fraction of the material derived from recycled sources and F$_U$ is the fraction of material from reused sources;

ii. The total amount of unrecoverable waste associated with a product:

$$W = W_0 + \frac{W_f + W_c}{2} \qquad (3)$$

W$_0$ is the amount of unrecoverable waste generated from material χ going to landfill or directed for energy recovery and is given by equation 4:

$$W_O = M \times (1 - C_R - C_U) \qquad (4)$$

where C$_R$ is the fraction of material χ being collected for recycling at the end of the product use phase and C$_U$ is the fraction of material going into the component reuse;
W$_C$ is the quantity of unrecoverable waste generated in the recycling process of material χ:

$$WC = M \times (1 - E_C \times C_R) \qquad (5)$$

where E$_C$ is the efficiency of the recycling process used for the material recycling at the end of the product use phase;
W$_f$ is the amount of unrecoverable waste generated to produce any recycled content used as feedstock:

$$WF = M \times \left((1 - E_F) \times \frac{F_R}{E_F}\right) \qquad (6)$$

where E$_F$ is the efficiency of the recycling process used to produce the recycled feedstock.

iii. The Linear Flow Index:

$$LFI = \frac{v+W}{2M+\frac{W_f - Wc}{2}} \qquad (7)$$

iv. The product utility:

$$X = \frac{L}{L_{av}} + \frac{U}{U_{av}} \qquad (8)$$

Where L is the product's actual average lifetime, L$_{av}$ is the actual average lifetime of an industry-average product of the same type, U is the actual average number of functional units achieved during the product use phase and U$_{av}$ represents the actual average number of functional units achieved during the use phase of an industry-average product of the same type.

v. The utility factor built as a function of the product utility X:

$$F(X)\,\frac{0.9}{X} = \qquad (9)$$

vi. The Material Circularity Indicator of a product is then calculated by:

$$MCI \times P = 1 - LFI \times F(X) \qquad (10)$$

The MCI has a simple scale of 0 to 1, with 0.1 indicating a linear process and 1 indicating a fully circular one. A result of less than 0.1 indicates a linear product with a lower-than-average utility.

RESULTS AND DISCUSSION

Characterization of Sludge Sample.

The sludge sample was characterized for physicochemical properties and the result presented in Table 1 below

Table 1: Physicochemical properties of sludge sample.

Parameter	Unit	Value
pH	-	6.24
Pb	mg/kg	95
N	mg/L (ppm)	86.80
P	mg/L (ppm)	150.62
K	mg/L (ppm)	265.00
Organic Carbon	%	1.62
Organic Matter	%	2.79

The physicochemical properties of the original sludge sample as obtained from Ahmadu Bello University water works are reported in Table 1. The pH of the sludge was 6.24. The slightly acidic pH is within the range acceptable for agricultural soils which is 5.5 – 7.5 (Odutola, 2019). pH is a master variable because it controls many chemical and biochemical processes operating within the soil. It is a measure of the acidity or alkalinity. The study of pH is very important in agriculture because it regulates plant nutrient availability by controlling the chemical forms of the different nutrients and also influences their chemical reactions. As a result, crop productivity is linked to soil pH value. A pH range of 6 to 7 is generally most favorable for plant growth because most plant nutrients are readily available. (USDA Natural Resources Conservation Service)

The initial lead concentration of the sludge was found to be 95mg/kg in comparison to the Plant Production and Protection Division (NSP) of the Food and Agriculture Division of the United Nations sets the standard for organic fertilizers Lead (Pb) content at a maximum of 100 mg/kg (Plant Production and Protection Division, 2022).

The sludge sample falls slightly short of the maximum acceptable limit for lead content thus safer limits can be actualized through remediation. The presence of heavy metals can pose a long-term environmental hazard once accumulated on land with the nutrient content of the sludge i.e., nitrogen, phosphorus, potassium, and organic carbon, and organic matter are also presented in Table 1.

Suitability of Abu Water Works Sludge As a Soil Conditioner

The sludge from Ahmadu Bello University Water Works as presented in Table 1 was found to have 86.80mg/L nitrogen, 150.62mg/L phosphorus, and 265mg/L potassium. Lone et al., (2013) applied sludge containing similar quantities of nutrients in loamy soil and observed that the composition of microelements (N, P, K) exhibited increased trends in the fertilizer and sludge amended treatments because these nutrients got incorporated into the soil resulting in their higher quantities. In an analysis of oil palm seedlings, Mohidin *et al.*, (2015) also observed similar NPK levels of 100ppm, 90ppm, and 300ppm respectively to give the best growth traits, biomass accumulation, and nutrient uptake.

Physicochemical and biological characteristics of agricultural soils, which are amended with the organics-rich sludge can be considerably improved, a reduced bulk density leads to an increased soil porosity and soil-air recirculation, as well as improved soil structure and water holding capacity. In addition, the application of sludge increases the concentration of soil humus. However, the organic carbon content of the sludge was found to be 1.62%, which is below the widely suggested soil organic carbon threshold of 2% for sustaining soil quality. (Musinguzi et al. 2013). Both excessive and insufficient Soil Organic Carbon levels can pose environmental threats, leading to pollution or loss of biodiversity. It is widely accepted that increasing soil organic matter by applying organic materials is a beneficial practice. A soil organic matter content of 2.79% shows to be more than the 1.20% that was reported by Egwu et al., 2018. Conversely, low Soil Organic Carbon levels can pose an environmental threat, as low fertility results in low biomass yield. Such levels can also lead to significant fertilizer loss due to low buffer or retention capacity. Organic matter of sludge enhances soil nutrient storage, soil biota, and diversity, as well as reduces exposure to erosion. High organic matter content facilitates the formation of stable organic complexes with humic acids, thus reducing metal availability A slow release of mineral elements from sludge to soil also changes the physical, chemical, and biological parameters of soil and benefits from increased gas exchange, better water infiltration, and its retention. The compounds of sludge are available for a longer period.

The use of sludge on agricultural land can be an interesting strategy to improve crop efficiency by increasing soil organic matter, fertility, and the presence of nutrients; in addition, sludge may also improve soil physical properties, especially in heavily and poorly structured soils. The spread of sludge on agricultural land also reduces the impact of loss of soil organic matter especially in areas prone to organic matter depletion and soil degradation due to environmental hazards like erosion. The development of a sustainable and integrated closed-loop system for the reuse of sludge in agricultural applications can be completely incorporated into the concept of a circular economy. In recent years, the European Commission has adopted an ambitious circular economy package to promote the reuse, recycling, and recovery of waste.

Characterization of Lemon Peel Extract

The lemon peels were also characterized for physicochemical properties and presented in Table 2 as shown below:

Table 2: Physicochemical properties of lemon extracts

Concentration (g/L)	pH	N (mg/kg)	% N	P (mg/kg)	% P	K (mg/kg)	% K
20	5.04	14	0.0014	172.14	0.0172	31	0.0031
60	5.13	112	0.0112	236.69	0.0237	170	0.017
100	5.21	478	0.0478	322.76	0.032276	210	0.021

The extracts were found to be slightly acidic having a pH level of 5.2 which satisfies the condition for the extraction of heavy metals. The mechanism of migration and transformation of heavy metals can be summarized as ion exchange, dissolution, and desorption (Lin and Chen 1998). Among the numerous influencing factors, pH is one of the main factors and the effect of pH on the speciation of heavy metals is of great significance to the migration and transformation of metals. The change in pH conditions in the system will have a certain impact on the migration and distribution of heavy metals (Zhang *et al* 2019). When the pH is lower than 3, the active sites (e.g. carboxyl groups) become protonated and thus are no longer available to attract positive metal ions from the solution.

The net negative surface charge of soils increases with increasing pH, resulting in higher affinity between soil surfaces and heavy metal ions (Harter and Naidu 2001). Further, pH changes the ion forms of metals adsorbed on soil surfaces where the hydrolysis of metal cations increases with increasing pH. In addition, soil pH also affects the solubility of heavy metals by influencing the surface potential, clay edge charge, ion-pair formation, the solubility of organic matter, and the stability of metal carbonates and phosphates (Appel and Ma 2002). In a word, due to these changes of heavy metals in adsorption, solubility, stability, etc., the extractability of heavy metals was affected strongly by soil pH, in which there is usually a marked decrease in the extraction of heavy metals with the increase in soil pH.

The lemon peel was found to also contain NPK nutrients which can potentially increase the available levels of nutrients in the soil.

Functional Properties of Lemon Peel Extract

FTIR analysis is essential for identifying some characteristic functional groups present in the extract (Abdolali et al., 2017). The figure below shows an FTIR analysis of the lemon peel to determine the functional groups that favor the lead extraction process.

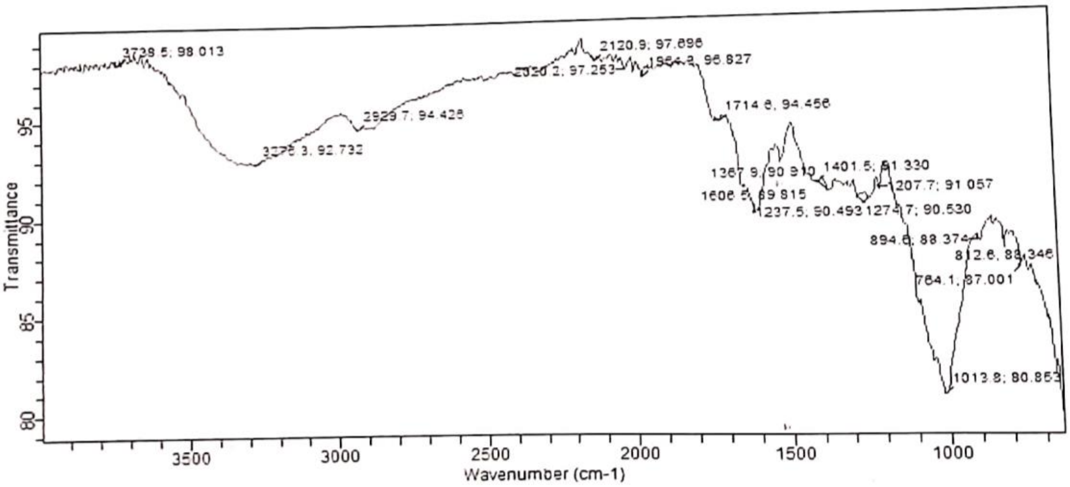

Figure 2: FTIR analysis of lemon peel

Several peaks were observed with different peaks corresponding to different functional groups and the relevant peaks are shown in Table 3 below. The hydroxyl, carboxyl, ether, and amide groups are the main functional groups in the sample and they have been identified as potential sites responsible for binding heavy metal ions to the biomass.

Table 3: Absorption peaks of lemon peels

Obtained peaks	Analysis
3276.3	Alcohols – H-bonded (–OH), Normal 'polymeric' OH stretch
2929.7	Carboxylic acids (–OH)
1714.6	C=O (aldehyde)
1606.5	C=C (alkene, aromatic, amino acids)
1237.5	Primary or secondary, OH in-plane bend, phenol or tertiary alcohol, OH bend
1013.8	Primary alcohol, C–O stretch, primary amine, CN stretch

The OH stretching vibrations occur within a broad range of frequencies indicating the presence of free hydroxyl groups and bonded OH bands of carboxylic acids (Ahmed et al., 2016). Broad absorption band in the region 3500–3000cm^{-1} corresponds to the characteristic O–H stretching vibration and hydrogen bond of the hydroxyl groups This band might be due to the inter/intramolecular hydrogen bonding of the fiber backbone (Singthong, *et al.,* 2014). Peaks around 2929 cm^{-1} can be assigned to stretching asymmetric vibration of the CH group. The peaks around 1636-1617 are assigned to carboxylic acid and alkyl carbonate C-OH of carboxyl and 1415-1406 cm^{-1} due to carbonate ion vibrations of lemon peel.

Peaks around 1069.66-1058.73 cm-1 are observed in all studied samples due to the stretching of the cellulose component (Marti, *et al.,* 2009). The presence of these polysaccharides represents an ally in the extraction of lead due to their structure which has the presence of groups such as alcohols, acids, phenolic hydroxides, aldehydes, and ethers that usually increase ion exchange capacities because they are polar compounds (Tovar *et al.,* 2015)

The wave number between 800 and 1200 in the tested peel samples represents the fingerprint region of fiber corresponding to CH3 deformation, C–O–C stretching, and O–H bending.

Table 4: Physicochemical and nutrient properties of the treated and untreated sludge

Property	Unit	Treated sludge	Untreated sludge
pH		6.0	6.24
N	%	0.45	86.80
P	%	0.12	150.62
K	%	0.3	265.00
OC	%	3.67	1.62
OM	%	6.31	2.79

After the extraction process with the waste lemon extract, it was observed that the organic carbon, nitrogen, phosphorus, and potassium significantly increased in the washed sludge as shown in Table 4. Minimizing nutrient loss is essential for achieving the reuse of sludge. In this regard, the extraction process may change the chemical properties as suggested by researchers (Ren *et al.,* 2015; Wang et al., 2015). Compared with the untreated sludge, significant increases in Organic carbon, Available Nitrogen, Phosphorus, and Potassium in the sludge were observed after washing. The increase in organic matter was also observed in previous studies using citric acid to treat sludge (Ren *et al.,* 2015; Wang *et al.,* 2015). This enhancement may be related to the lemon peel residues with rich organic carbon and nutrients (Fend *et al.,* 2018). The improvement can also be attributed to the transformation and dissolution of unavailable Phosphorus and Potassium added to the available Phosphorus and Potassium under acidic washing conditions (Ren *et al.,* 2015). Citric acid has been reported to decrease total nitrogen, total phosphorus, and total potassium during the washing process (Ren *et al.,* 2015; Wang *et al.,* 2015). These results reveal that the lemon peel extract can effectively moderate the effects of washing on sludge chemical properties. The treated sludge exhibited higher levels of nutrients and hence has the potential for application to soil amendment and manure.

The pH of the treated sludge slightly decreased to 6.0 after washing due to the slightly acidic condition of the waste lemon extract. In the case of a commercial acid, the acid might act as a chelating agent to capture the metal ions absorbed on the surface of sludge particles. The hydrogen ions might take up the sludge active sites that used to be occupied by the lead ions, resulting in a decrease in hydrogen ion concentration (Lestan *et al.,* 2008). The pH of the waste lemon extract was higher than the usual pH of commercial acids and the organic constituents in the waste lemon extract reacted with the nitrogenous substances in the soil, causing a slight decrease to a pH of 6 which is near neutral and ideal for plant growth.

Circularity Assessment

To ascertain the MCI of the lead-remediation process using waste lemon peel, Ahmadu Bello University is considered a sustainable and closed-loop system where a regenerative model functions, this is illustrated in Figure 3 below where the virgin feedstock is the lemon peel which is sustainably derived from a lemon plantation in the University's orchard. The virgin feedstock is then used to manufacture the product, which is the lemon peel extractant. The product is further used to remediate lead-contaminated sludge which is a by-product of the Ahmadu Bello University Water Treatment Plant. The remediated sludge is then utilized as a soil conditioner on the lemon plantation to aid performance and produce lemons which generates waste lemon peels that restart the loop.

The by-product derived from producing the extractant (i.e residual lemon peel powder) is an organic material that can be composted and reused for agricultural purposes on the lemon plantation, thus the functional units (U) derived from the product is 2. i.e. as an extractant and as a compost. The functional units (U_{av}) for an industry average product (chemical reagent) utilized to remediate lead-contaminated sludge for agricultural application is 1 as no other related benefit to the closed loop system is derived.

The average lifetime of the product (L) which is the dried lemon peel is 3 years (Garden, 2022) while the average lifetime of an industry average product. i.e. the shelf life of a chemical reagent is 2 years from the date of opening (pharmaguidelines.com).

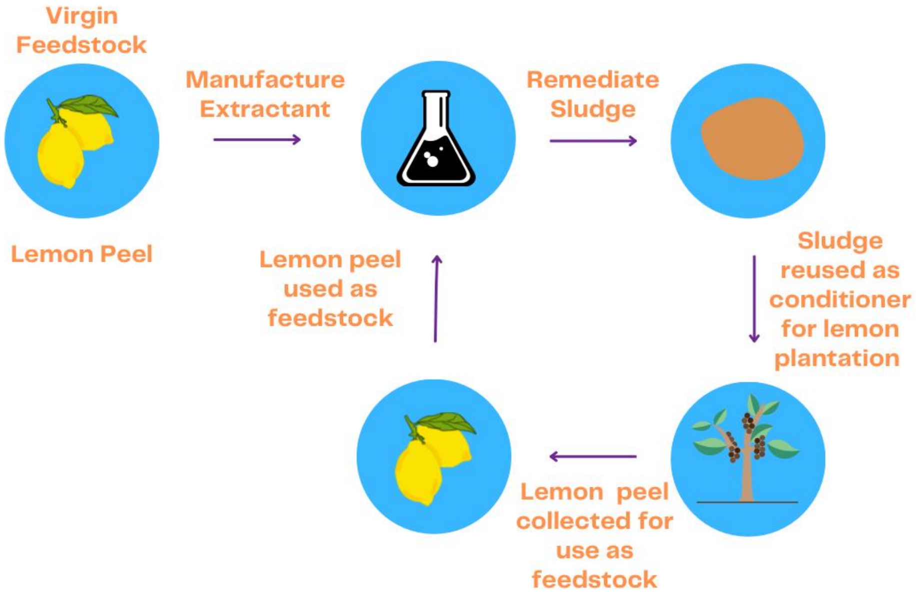

Figure 3: Modified MCI of the ABU closed loop system.

The calculation of the MCI is calculated as follows:

i. The amount of the virgin feedstock material:

$V = M \times (1 - F_R - F_U)$

M (mass of the material) = 100g (mass of lemon peel that yielded highest removal efficiency)

F_R (fraction of the material derived from recycled sources) = 0

F_U (fraction of material from reused sources) = 0

$100 \times (1 - 0 - 0)$

V = 100

ii. The total amount of unrecoverable waste associated with a product:

$W = W_0 + \frac{W_f + W_c}{2}$

W_o is the amount of unrecoverable waste generated from materials going to landfill or directed for energy recovery and is given by:

$W_O = M \times (1 - C_R - C_U)$

C_R (fraction of material being collected for recycling) = 0

C_U (fraction of material going into the component reuse) = 90/100 = 0.9

$W_O = 100 \times (1 - 0 - 0.9)$

$W_o = 10$

iii. Wc is the quantity of unrecoverable waste generated in the recycling process of the material:

$W_C = M \times (1 - E_C \times C_R)$

W_c = 0 (no uncoverable waste was generated due to recycling)

W_f is the amount of unrecoverable waste generated to produce any recycled content used as feedstock:

$W_F = M \times ((1 - E_F) \times F_R / E_F)$

W_f = 0 (no unrecoverable waste was generated to reproduce recycled content as feedstock)

Therefore from equation (3),

$W = 10 + \frac{0+0}{2}$

W = 10

iv. The Linear Flow Index:

$$\text{LFI} = \frac{v + W}{2M + \frac{W_f - Wc}{2}}$$

$$\text{LFI} = \frac{100+10}{2\times100+\frac{0-0}{2}}$$

LFI = 0.55

v. The product utility:

$X = \frac{L}{L_{av}} + \frac{U}{U_{av}}$

L (product actual average lifetime in years) = 3

L_{av} (actual average lifetime of an industry-average product in years) = 2

U (actual average number of functional units achieved during the product use phase) = 2

U_{av} (actual average number of functional units achieved during the use phase of an industry-average product) = 1

Therefore $X = \frac{3}{2} + \frac{2}{1}$

X = 3

vi. The utility factor built as a function of the product utility X:

$$F(X) = \frac{0.9}{X}$$

$F(X) = \frac{0.9}{3}$

F(X) = 0.3

vii. The Material Circularity Indicator of a product is then calculated by:

MCI = 1 – LFI × F(X)

MCI 1 – 0.55×0.3

MCI = 0.835

The MCI has a simple scale of 0 to 1, with 0.1 indicating a linear process and 1 indicating a fully circular one. A result of less than 0.1 indicates a linear product with a lower-than-average utility. An MCI of 0.835 indicates a highly circular system.

CONCLUSIONS

The following conclusions were drawn from the study:

i. The characterization of raw sludge sample revealed a pH of 6.24 which is slightly acidic and within acceptable range for agricultural soils.

ii. The hydroxyl, carboxyl, ether, and amide groups are the main functional groups in the sample and they have been identified as potential sites responsible for binding heavy metal ions to the biomass.

iii. Waste Lemon Peels were effective in bringing Lead concentration in the sludge from 95mg/kg to 9.1mg/kg representing a 90.5% removal efficiency.
iv. The Material Circularity Indicator of 0.835 indicated a highly circular system

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