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ORIGINAL RESEARCH

Preliminary Investigation on Metal Tolerance and Antibiotic Resistance Profiles of Indigenous Bacteria Isolated from Blast-Impacted Soil in Lokoja, Nigeria

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ABSTRACT

Soil contamination with heavy metal causes serious environmental threats, particularly in mining areas affected by blasting. The bacterial diversity, heavy-metal tolerance, and bacteria antibiotic susceptibility were investigated from a previously active blast-site soil in Lokoja, Nigeria. Soil physicochemical analysis revealed a slightly alkaline pH (8.6) and appreciable organic matter content (8.87%). Six bacterial isolates were isolated from previously active blast site in Crusher, Lokoja and identified as *Bacillus cereus*, *Bacillus subtilis*, *Pseudomonas luteola*, *Escherichia coli*, and two species of *Staphylococcus*. Metal resistance screening showed that most isolates were highly tolerant to lead and arsenic, while cadmium exerted stronger inhibitory effects. Cadmium gradient and Minimum Inhibitory Concentration (MIC) analyses confirmed a response that was dose-dependent, with cadmium showing the lowest tolerance thresholds. *Bacillus* spp. and *Pseudomonas luteola* exhibited the highest overall metal tolerance with *B. subtilis* having the highest MIC values for cadmium and lead (50mg/mL, 500mg/mL), *B. cereus* for lead (500mg/mL) and *P. luteola* for cadmium (50mg/mL). All isolate showed growth at the highest tested arsenic concentration (700mg/mL) except for the second *Staphylococcus* species - *Staphylococcus2* (300mg/mL). Antibiotic susceptibility testing indicated that the isolates were highly sensitive, with a single resistance recorded by Staphylococcus1 to the antibiotic Co-Trimoxazole. This study revealed that blast impacted soils host indigenous bacteria tolerant to heavy metals which have strong bioremediation potentials.

Keywords: Heavy metal, Cadmium, Lead, Arsenic, Blast site, Metal tolerant bacteria.

INTRODUCTION

Heavy-metal contamination poses a growing environmental threat, especially in regions affected by mining, explosive detonations, and industrial waste. Unlike organic pollutants, heavy-metals like arsenic (As), and lead (Pb), stay in the soil, accumulate and exert toxic effects on all living

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organisms (Zulfiqar et al., 2023). Naseri et al. (2021) and Jomova et al. (2025) linked exposure to these metals with carcinogenic, neurotoxic, teratogenic, and endocrine-disrupting effects in organisms. For instance, reported that As and Cd, potent carcinogens, disrupt deoxyribonucleic acid (DNA) synthesis and repair mechanisms Naseri et al. (2021).

Blast related activities such as mining, construction, and military operations introduce heavy metals into the environment through physical and chemical processes. This is achieved through rock fragmentation and dispersal of fine particles that often contain metals such as lead, cadmium, and arsenic over a wide area during explosions environments (Bhandari, 2013). The extreme temperatures generated can also vaporize these metals, which condenses into fine particulates that settle onto surrounding soils. In addition, airborne dust and debris generated during blasting can be transported over considerable distances before deposition, leading to secondary contamination of adjacent environments (Bhandari, 2013).

Microorganisms inhabiting contaminated sites often develop tolerance to elevated levels of heavy metals through efflux pumps, sequestration, enzymatic detoxification, and biofilms (Barik et al., 2021; Nanda et al., 2019; Nnaji et al., 2024; Shukla et al., 2017). These organisms hold promise for bioremediation and ecosystem restoration. However, there is increasing concern regarding the presence of resistance to antibiotic among bacteria tolerant to heavy-metal, as metal-contaminated environments may apply selective pressure for multi-drug-resistant strains (Jimoh et al., 2025, Squadrone, 2020).

Despite the reported occurrence of metal contamination in many Nigerian urban and peri-urban landscapes (Adewale et al., 2023; Adeyi & Babalola, 2017; Akinleye et al., 2022; Iwegbue, & Martincigh, 2018; Famuyiwa et al., 2022), few studies have characterized indigenous metal-tolerant bacteria from explosive-blast environments (Emmanuel et al., 2017, Ibrahim et al., 2021). Lokoja, located at the geological confluence, has experienced recurrent blasting activities, making its soils a potential hotspot for heavy-metal accumulation and adaptive microbes. This study isolated and identified soil bacteria tolerant to arsenic, cadmium, and lead from a former blast location, determining their minimum inhibitory concentrations (MICs) for each metal and

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assessing antibiotic susceptibility profiles. As one of the few characterization study from blast sites in Lokoja, this work reveals ecological adaptation of indigenous bacteria and their resistance profile in metal-contaminated environments.

MATERIALS AND METHODS

Study Area and Sample Collection

The study was conducted in Lokoja, the capital of Kogi State, a region characterized by extensive mining and rock-blasting activities. Three soil samples were aseptically collected at a depth of 0–15 cm using a randomized design from a former blast site in Crusher, Lokoja (7.85003°N, 6.67971°E), where blasting operations had previously taken place. Approximately 500 g of soil was obtained for analysis. The samples were put into sterilized bags, properly labeled, and moved to the laboratory on ice pack to the laboratory for analysis. The soil was sieved to achieve uniform size and remove unwanted stick and dirt fragments.

Physicochemical Analysis of Soil

Physicochemical parameters (pH and organic matter content) were analyzed at the Chemistry Laboratory, Kogi State Polytechnic, Lokoja. The methods outlined by Okorie et al. (2024) were considered for this study.

Briefly, 10 mls of sterile distilled water was combined with 10 g of soil sample (1:1 w/v) in a clean beaker, stirred for 30 minutes, and allowed to equilibrate. A calibrated digital pH meter with model number PH-009(1). A (using standard buffers at pH 4, 7, and 10) was inserted in the soil mixture, and reading was taken. Organic matter (OM) was estimated using gravimetric method. Ten grams of soil was placed on a pre-weighed filter paper, and the combined weight recorded. The sample was oven-dried in a crucible for 24 h at a temperature of 105 °C. After which samples were left to cool in a desiccator then reweighed. OM was calculated from the loss in weight after drying using the formula below.

$$OM\ (\%) = [(\text{wet wt} - \text{dry wt})/\text{wet wt}] \times 100$$

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Isolation and Purification of Bacterial Isolates

Sample dilution and bacterial isolation was done using a method revised from Ibrahim et al. (2021). 1 g of soil sample was placed into 9 mL of sterile saline (0.85%), vortexed intermittently, and left to stand for 30 minutes to release microorganisms from soil particles followed by preparation of a seven-fold serial dilution. From each dilution, 0.1 mL was aliquoted on sterile agar plates (Nutrient, blood, and MacConkey agar). The plates were incubated at 37 ^{o}C for 24 - 48 hours. Discrete colonies were repeatedly sub-cultured to obtain pure isolates.

The purified isolates were identified via physical and biochemical analyses as described by Agbo et al., (2019). These include colony morphology, gram-staining, catalase, indole, citrate, urease, oxidase, and triple sugar ion tests. Bacterial isolates were smeared on clean glass slides, allowed to air-dried, and then fixed using heat. Crystal violet was applied to the smears for 1 min, rinsed, and treated with a solution of iodine for 1 min. The slide was decolorized using acetone, left for 30 s and rinse immediately. It was then counterstained with safranin for 30 s, rinsed, blot-dried, and observed under a microscope for Gram reaction and cell morphology.

Biochemical Analyses

Biochemical analyses were performed on the bacterial isolates using standard microbiological procedures (Barrow and Feltham, 2003; Holt et al., 1994). A drop of colony suspension was placed on a clean glass slide, and a drop of hydrogen peroxide was added. Immediate bubble formation indicated a positive catalase reaction, while the absence of bubbles indicated a negative result.

The isolated bacteria were inoculated into tryptone broth which was incubated for 24 hours at 37°C. After incubation, a few drops of Kovac's reagent were added to the broth. A positive result was indicated by the formation of a bright red layer at the top of the broth, confirming the production of indole from the breakdown of tryptophan. A negative result was the absence of a red layer.

The isolates were also streaked lightly onto the surface of a Simmons citrate agar slant. The slants were incubated at 37 °C for 24 hours. A positive result was indicated by bacterial growth on the slant and a color change from green to blue, which signifies the utilization of citrate as the sole

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carbon source. A negative result was indicated by no growth on the slant and no colour change. Triple Sugar Iron (TSI) Analysis was performed on the isolates by stabbing and streaking isolates into TSI agar in test tubes and incubated for 24 hours at a temperature of 37 ^{0}C. Results were interpreted based on glucose, lactose/sucrose fermentation, gas production and H_2S formation.

Oxidase Analysis was conducted by smearing bacterial colonies onto filter paper impregnated with oxidase agent (tetramethyl-p-phenylenediamine). The development of a dark purple colour within 10–30 seconds indicated a positive result, whereas no colour change or delayed reaction beyond 60 seconds indicated a negative result (Cappuccino and Sherman, 2014).

For urease activity, isolates were inoculated into urea broth and incubated at 37 °C for 24 h. A positive result was indicated by a colour change from yellow to pink or red due to ammonia production, while a negative result remained yellow (Barrow and Feltham, 2003).

Preparation of Heavy-Metal Stock Solution

1000 mg/L of the following heavy metal stock solutions were prepared following standard procedures: lead (II) acetate, cadmium (II) acetate, and sodium arsenate. The appropriate mass of each salt was weighed based on its molar mass to achieve the final stock concentration. 1 g of each salt was dissolved in 1 L of distilled water, and filter-sterilized. The prepared solutions were stored in sterile, labeled bottles at 4 °C until required. Subsequent working concentrations were made from the stock solutions using the formula below:

$$V_1 = C_2V_2 \div C_1$$

Where; C_1= Initial concentration (stock)

C_2 = Desired concentration

V_1 = Required volume of stock solution

V_2 = Final dilution volume

Metal Resistance Tests

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Preliminary metal resistance testing was conducted using an agar well diffusion assay adapted from Tomova et al. (2015). A 0.05% (w/v) solution of each metal salt (lead, cadmium, and arsenic) was prepared. Nutrient agar plates, inoculated with standardized bacterial suspensions, were aseptically bored with 6 mm wells by a sterile cork borer. 100 µL of all metal solutions were aliquoted into the wells. The plates were then incubated at 37 °C for 48 hours and the zones of inhibition (mm) were measured. Isolates showing clear zones (≤1 mm) were categorized as resistant.

MIC Analysis of Selected Heavy-Metals

The MIC was the lowest heavy-metal concentration showing no visible bacterial growth. It was carried out using nutrient broth added with increasing heavy metals concentrations as follows:

- Lead (Pb): 200, 300, 400, 500, 600, 700 mg/L
- Cadmium (Cd): 10, 20, 30, 40, 50, 60 mg/L
- Arsenic (As): 200, 300, 400, 500, 600, 700 mg/L

Test-tubes were inoculated with standardized bacterial cultures, incubated at a temperature of 37 ^{0}C for 24 h. After which the tubes were assessed for bacterial growth (turbidity).

Cadmium Gradient Resistance Assay

Due to cadmium's known high toxicity at low concentrations, a gradient resistance assay as described by Eghomwanre et al. (2016) was used. Nutrient plates were inoculated with bacterial suspensions with varying cadmium concentrations (20, 15, 10, 5 mg/L) introduced into the wells (100 µL each). The plates were incubated at 37 ^{0}C temperature for 24 hours. After incubation, the zones of inhibition round each well were measured and recorded in millimeters.

Antibiotic Susceptibility Screening

The antibiotic susceptibility analysis was done via Kirby-Bauer disk diffusion method as described by CLSI (2020). Bacterial suspensions of the isolates were prepared and standardized to 0.5 McFarland turbidity. The suspensions were swabbed on Mueller-Hinton agar plates. Commercial antibiotic disks (tetracycline, amikacin, ciprofloxacin, trimethoprim-sulfamethoxazole, and

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tigecycline) were aseptically placed on the agar surface. The plates were incubated for 24 h at a temperature of 37 ºC. The inhibition zones round each disk were measured in millimeters. The results were interpreted according to CLSI standards to categorize isolates as susceptible, intermediate, or resistant.

Statistical Analysis

Data generated from physicochemical analysis, metal susceptibility assays, MIC determination, and antibiotic susceptibility tests were entered into Microsoft Excel 2019. Graphical presentations, including bar charts and frequency distributions, were carried out to illustrate variations in MIC values and inhibition zone diameters among isolates. The zones of inhibition (mm) obtained for the bacterial isolates at different cadmium concentrations were subjected to statistical analysis using a two-way analysis of variance (ANOVA). Cadmium concentration and bacterial isolate were treated as independent factors, while the zone of inhibition served as the dependent variable. Differences were considered statistically significant at $p < 0.05$. All analyses were carried out using the IBM SPSS Statistics version 23.

RESULTS

The physicochemical analysis of the soil sample presented in Table 1 showed a moderately alkaline pH at 8.60 and a high organic matter content of 8.87%.

Table 1: Soil Physicochemical Parameter

Parameter	Value
pH	8.60
Organic Matter (%)	8.87

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A total of six (6) bacterial isolates were recovered from the sample site. Biochemical characterization revealed the presence of Gram-negative bacteria and Gram-positive in the sample. Based on standard biochemical analyses (indole, oxidase, urease, citrate utilization, catalase, and Triple Sugar Iron reactions), six bacterial isolates were presumptively identified (Table 2). Isolate1 was identified as *Pseudomonas luteola*, Isolate2 as *Escherichia coli*, Isolates3 and 6 as *Staphylococcus* spp., Isolate4 as *Bacillus cereus*, and Isolate5 as *Bacillus subtilis*.

Table 2: Physical and Biochemical Characteristics of Isolates

Test / Characteristic	**Isolate1**	**Isolate2**	**Isolate3**	**Isolate4**	**Isolate5**	**Isolate6**
Gram reaction	Gram -ve	Gram -ve	Gram +ve	Gram +ve	Gram +ve	Gram +ve
Cell morphology	Rod	Rod	Cocci	Rod	Rod	Cocci
Indole	-	+	*	-	-	*
Oxidase test	-	-	*	+	+	*
Urease test	-	-	*	-	-	*
Citrate utilization	+	-	*	-	+	*
Catalase test	+	+	+	+	+	+
H_2S production	-	-	*	*	*	*
Gas production	-	+	*	*	*	*
TSI reaction (slant/butt)	Red / Red (K/K)	Yellow / Yellow (A/A)	*	*	*	*
Presumptive identity	*Pseudomonas luteola*.	*Escherichia coli*	*Staphylococcus* spp.	*Bacillus cereus*	*Bacillus subtilis*	*Staphylococcus* spp.

*Not applicable, + positive, - negative

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Preliminary metal susceptibility screening revealed varying levels of tolerance among the six bacterial isolates toward cadmium, lead, and arsenic. Zones of inhibition are presented in Table 5. Cadmium showed the greatest inhibitory effect on the isolates, with *Bacillus cereus* exhibiting the greatest susceptibility (32 mm), followed by *Escherichia coli* (22 mm) and *Staphylococcus* spp2. (18 mm). In contrast, lead and arsenic produced little to no inhibitory effect on most isolates, with zones ranging from 0 to ≤1 mm, except for *Bacillus subtilis*, which showed a measurable zone of inhibition (7 mm) against arsenic.

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Table 3: Zones of Inhibition (mm) of Bacterial Isolates Exposed to Cadmium, Lead, and Arsenic

Isolates	Cadmium (mm)	Lead (mm)	Arsenic (mm)
Pseudomonas luteola	16	≤1	0
Echerichia coli	22	0	0
Staphylococcus spp	10	0	0
Bacillus cereus	32	≤ 1	≤ 1
Bacillus subtilis	8	0	7
Staphylococcus spp2	18	0	≤ 1

To further assess cadmium tolerance, isolates were tested against a gradient of cadmium concentrations (5-20 mg/L). Zones of inhibition decreased progressively with decreasing metal concentration, as shown in Table 6. At the highest concentration (20 mg/L), all isolates showed measurable zones of inhibition, with *Bacillus cereus* exhibiting the greatest sensitivity (16 mm), followed by *Escherichia coli* (11 mm) and *Staphylococcus* spp2. (10 mm). As cadmium concentration decreased from 15 mg/L to 5 mg/L, the zones of inhibition progressively reduced across all isolates, and little to no inhibition was observed at 5 mg/L.

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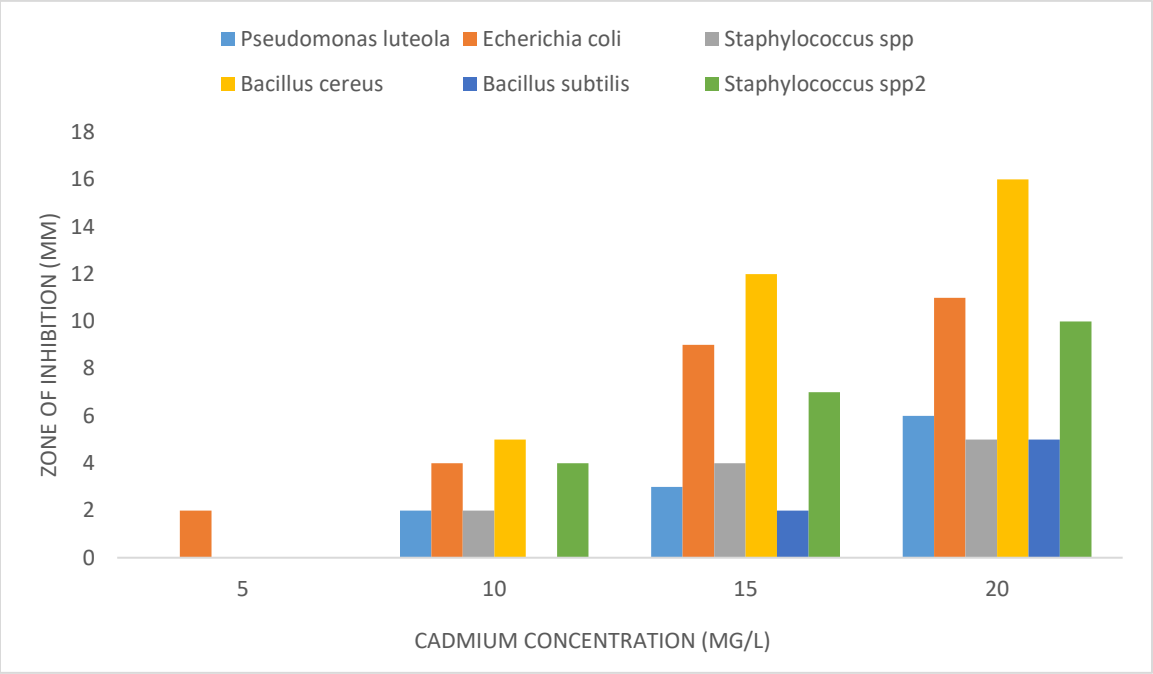


Figure 1: Zones of Inhibition (mm) of Bacterial Isolates at Different Cadmium Concentrations

A two-way ANOVA without replication revealed that cadmium concentration had a significant effect on the zones of inhibition ($F = 21.67$, $p < 0.05$). Similarly, there was a significant difference among the bacterial isolates ($F = 6.78$, $p < 0.05$).

Table 4: ANOVA Summary Table

Source of Variation	SS	df	MS	F
Concentration	230.33	3	76.78	21.67
Isolates	120.17	5	24.03	6.78
Error	53.17	15	3.54	—
Total	403.67	23	—	—

SS: Sum of Squares; df: degree of freedom; MS: Mean Square; F: F ratio

The MIC values for cadmium, lead, and arsenic against the six bacterial isolates are presented in Tables 5-7. The assays revealed variable heavy-metal tolerance among the isolates. Cadmium revealed the most inhibition, all isolates exhibited growth at 10 mg/L, while increased

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concentrations progressively inhibited bacterial growth. *Pseudomonas luteola* and *Bacillus subtilis* demonstrated the highest tolerance, maintaining growth up to 50 mg/L before complete inhibition at 60 mg/L. *Escherichia coli*, *Bacillus cereus*, *Staphylococcus* spp were inhibited at lower concentrations, with no growth observed from 20-40 mg/L for all except *Pseudomonas luteola* (Table 5).

Lead tolerance was higher, with MICs between 400 and 600 mg/L (Table 6), and arsenic tolerance was the highest, as five of six isolates grew up to 700 mg/L, except for *Staphylococcus* spp2, which was inhibited at 400 mg/L (Table 7)

Table 5: Minimum Inhibitory Concentration of Cadmium for Bacterial Isolates

Cadmium (mg/L)	*Pseudomonas luteola*	*Escherichia coli*	*Staphylococcus* spp	*Bacillus cereus*	*Bacillus subtilis*	*Staphylococcus* spp2
10	+	+	+	+	+	+
20	+	–	+	+	+	+
30	+	–	+	+	+	–
40	+	–	–	–	+	–
50	+	–	–	–	+	–
60	–	–	–	–	–	–

+ (Growth) - (No growth)

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Table 6: Minimum Inhibitory Concentration of Lead for Bacterial Isolates

Lead (mg/L)	*Pseudomonas luteola*	*Escherichia coli*	*Staphylococcus* spp	*Bacillus cereus*	*Bacillus subtilis*	*Staphylococcus* spp2
200	+	+	+	+	+	+
300	+	+	+	+	+	+
400	+	–	+	+	+	+
500	–	–	–	+	+	+
600	–	–	–	–	–	–
700	–	–	–	–	–	–

+ (Growth) - (No growth)

Table 7: Minimum Inhibitory Concentration of Arsenic for Bacterial Isolate

Arsenic (mg/L)	*Pseudomonas luteola*	*Escherichia coli*	*Staphylococcus* spp	*Bacillus cereus*	*Bacillus subtilis*	*Staphylococcus* spp2
200	+	+	+	+	+	+
300	+	+	+	+	+	+
400	+	+	+	+	+	–
500	+	+	+	+	+	–
600	+	+	+	+	+	–
700	+	+	+	+	+	–

+ (Growth) - (No growth)

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Antibiotic Susceptibility

The antibiotic susceptibility profiles of the isolates (susceptible, intermediate, resistance) were interpreted based on zone diameter breakpoints specified by Clinical and Laboratory Standards Institute (CLSI), 2020. The majority of the isolates were susceptible to the tested antibiotics, with only a few exhibiting intermediate patterns and one resistant pattern. All isolates were susceptible to amikacin. Resistance was observed only to co-trimoxazole among *Staphylococcus* spp. Intermediate susceptibility was observed with ciprofloxacin in *Escherichia coli* and *Staphylococcus* spp. 2, as well as with tigecycline in *Staphylococcus* spp. and *Bacillus subtilis*. All isolates remained susceptible to tetracycline.

Table 8: Antibiotic Susceptibility Profiles of Bacterial Isolates

ISOLATES	TET	CIP	AK	SXT	TGC
Pseudomonas luteola	S	S	S	S	S
Echerichia coli	S	I	S	S	S
Staphylococcus spp	S	S	S	R	I
Bacillus cereus	S	S	S	S	S
Bacillus subtilis	S	S	S	S	I
*Staphylococcus spp*2	S	I	S	S	S

R – resistance, I – Intermediate, S – Susceptible,

TET: Tetracycline, CIP: Ciprofloxacin, AK: Amikacin, TGC: Tigecycline, SXT: Co-Trimoxazole

DISCUSSION

The soil from the blasted site exhibited a slightly alkaline pH (8.6), which is conducive to the growth of metal-tolerant bacteria. Alkaline conditions generally reduce the solubility and toxicity of many heavy metals, thereby enhancing microbial survival (Fernández-Calviño and Bååth, 2016; Lu et al., 2020). Under neutral to alkaline conditions, lead (Pb) is strongly adsorbed onto organic matter and clay minerals; however, at lower pH levels, its adsorption capacity declines, resulting in increased solubility and bioavailability (Keçeci, 2020) while Cadmium (Cd), is more mobile and highly sensitive to pH variations than lead. As pH increases, cadmium tends to precipitate as

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$Cd(OH)_2$ or becomes adsorbed onto soil particles, thereby reducing its bioavailability (Loganathan, et al., 2012). In contrast, Arsenic (As), exhibits a different behavior due to its anionic nature. Under alkaline conditions, arsenic desorption is enhanced due to competition with hydroxyl ions (OH^-), leading to increased mobility and bioavailability (Campbell, et al., 2014). Furthermore, the relatively high organic matter content (8.87%) likely supported bacterial growth by improving nutrient availability and providing additional binding sites for metal immobilization.

Six distinct bacterial isolates were recovered from the soil sample, with *Bacillus* spp. and *Staphylococcus* spp. being the most prevalent. These genera are frequently linked to stressed or contaminated environments, as documented in prior studies (Adeleye et al., 2019; Hou et al., 2022).

The presence of *Bacillus* and *Pseudomonas* species within the soil aligns with prior reports of their dominance in metal-polluted soils, attributed to their robust stress-response mechanisms such as spore formation (*Bacillus*), efflux systems, and biofilm production (*Pseudomonas*) (Fakhar, 2022; Teitzel and Parsek, 2003).

The heavy metal resistance profiles revealed varying degrees of tolerance across isolates. Inhibition zones for cadmium were generally higher than those for lead and arsenic, reflecting the higher toxicity of cadmium at lower concentrations (Rahman and Singh, 2019, Satarug et al., 2011). In the cadmium gradient resistance assay, zones of inhibition increased progressively with rising cadmium levels, indicating a clear dose-dependent toxic effect of cadmium which was in line with results gotten by Eghwonwamre et al., 2021. The significant differences observed among the isolates indicate variability in their tolerance to cadmium exposure. *Bacillus cereus* exhibited the highest susceptibility, while *Bacillus subtilis* appeared more resistant, suggesting possible differences in their physiological or genetic mechanisms of metal tolerance. The relatively low error variance observed in the ANOVA indicates that most of the variation in the data was attributable to the experimental factors (concentration and isolates), thereby strengthening the reliability of the findings.

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The MIC results corroborated the inhibition zone findings and revealed a clear hierarchy of metal tolerance among the bacterial isolates. Arsenic exhibited the highest tolerance thresholds, whereas cadmium showed the lowest. *Bacillus subtilis* exhibited the greatest cadmium tolerance, as shown by small inhibition zones and growth up to 50 mg/L in MIC assays. This demonstrates that *Bacillus subtilis* has a high potential for application in the bioremediation of cadmium-polluted soil. On the other hand, *Escherichia coli* showed lower tolerance, with complete inhibition at 20 mg/L. Lead tolerance across isolates was moderate, with most organisms inhibited between 400-500 mg/L. Arsenic tolerance was notably high in nearly all isolates, with sustained growth up to 700 mg/L in several cases, suggesting intrinsic or acquired arsenic-resistance determinants such as efflux pumps or arsenate reductases. The consistent growth of most isolates at elevated arsenic concentrations aligns with previous findings that arsenic, though toxic, allows broader microbial tolerance ranges due to widespread ars operons among soil bacteria (Ben Fekih et al., 2018; Bhardwaj, 2022). These differences may be attributed to metal-specific toxicity mechanisms. Cadmium on the other hand is known to disrupt essential enzymatic systems at minimal concentrations (Genchi et al., 2020; Rani et al., 2014), whereas arsenic detoxification is more common among environmental bacteria (Diba et al., 2023; Dunivin et al., 2019; Yoon et al., 2009).

Antibiotic susceptibility testing revealed that most isolates remained susceptible to the tested antimicrobial agents, particularly tetracycline, ciprofloxacin, amikacin, and co-trimoxazole. Resistance was rare, observed only for *Staphylococcus* spp against tigecycline. The absence of widespread antibiotic resistance is notable given the high metal tolerance exhibited by several isolates. This contrasts with the widely reported expectation of cross-resistance between heavy metals and antibiotics, often attributed to co-selection mechanisms such as efflux pumps, plasmid-mediated resistance genes, and oxidative stress response pathways. (Gillieatt and Coleman, 2024; Sincak et al., 2023; Singh et al., 2024). However, lack of co-resistance pattern between heavy metals and antibiotics in this study suggests that the isolates may possess metal-specific tolerance traits without concurrent antibiotic resistance determinants, or that the environmental contamination at the site did not include significant exposure to antimicrobial residues.

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Generally, the findings strongly support the potential of the isolated bacteria, particularly *Bacillus cereus*, *Bacillus subtilis*, *Pseudomonas luteola*, and metal-tolerant *Staphylococcus* spp. as promising candidates for bioremediation of cadmium, lead, arsenic contaminated soils. Their demonstrated tolerance to cadmium, lead, and arsenic shows their metabolic resilience and indicates possible mechanisms such as metal sequestration, biosorption, enzymatic detoxification, or efflux-based resistance. The alkaline pH and high organic content of the soil from the former blast site may further enhance their remediation capacity by improving microbial activity and reducing the bioavailable fractions of metals. The result of this study reveals the ecological adaptability of indigenous bacteria and provide a scientific basis for developing bioremediation strategies tailored to contaminated sites in Nigeria and similar environments.

CONCLUSION

This study shows that blast-impacted soils in Lokoja harbor diverse bacteria with high tolerance to arsenic and lead. Predominant genera (*Bacillus* and *Staphylococcus*) exhibit strong adaptations that enable survival under severe heavy metal stress. Minimum inhibitory concentration assays identified *Bacillus cereus*, *Bacillus subtilis*, and *Pseudomonas luteola* as the most resistant isolates. Notably, these strains remain largely susceptible to common antibiotics, suggesting limited co-selection of antibiotic resistance tolerance to heavy-metal. The results highlight the strong bioremediation potential of these indigenous bacteria for sustainable cleanup of sites contaminated with heavy-metal in Nigeria.

However, these findings are subject to certain limitations, including the absence of experimental replicates, lack of molecular identification of the isolates, and the absence of quantitative analysis of heavy metals in the soil samples. These constraints may limit the comprehensiveness and generalizability of the results.

Despite these limitations, the findings highlight the strong bioremediation potential of these indigenous bacteria for the sustainable remediation of heavy metal contaminated sites in Nigeria. Further studies employing 16S rRNA sequencing, qPCR analysis of resistance genes, and pilot-

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scale field trials are recommended to confirm the underlying mechanisms and evaluate practical efficacy while addressing the limitations of this study.

AUTHORS' CONTRIBUTION

All authors contributed significantly to this study and approve the final manuscript. Contributions are specified as follows: Conceptualization and study design by Adams E. E.; Methodology by Adams E. E.; Data collection/investigation by Adams E. E., Olundu, P. S., Ojonugwa, J. M., Ojonugwa, J. O., Olorundare, B. E., Abdulrahim, A., Otaru, B.; Data analysis and interpretation by Adams E. E., Ojonugwa, J. M., Ojonugwa, J. O., Olorundare, B. E., Abdulrahim, A., Otaru, B.; Drafting of the manuscript by Adams E. E.; Critical revision of the manuscript by Adams, E. E., Olundu, P. S.

CONFLICT OF INTEREST

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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