



Occupational Exposure to Quarry Dust and Progressive Systemic Toxicity in Animal Models Exposed to Two Quarry Sites in Ebonyi State, Nigeria

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ABSTRACT

Assessment of the health risks of occupational exposure to quarry dust is a public health priority, because quarry industry workers are usually exposed to respirable particulates of the dust over a long duration, which could have serious harmful effects to respiratory and non-respiratory organ systems. This study investigated some organs and biochemical effects of long-term exposure to quarry dust using a randomized controlled animal model. Seventy-two (72) male guinea pigs (800 - 1200 g) were exposed to quarry dust at Umuoghara and Amoffia-Ngbo quarry sites in Ebonyi State, Nigeria, for the durations of 3, 6, 9, and 12 months. The animals were randomly divided into three groups of 24 animals each and labeled UMR for Umuoghara quarry site, AMN for Amoffia-Ngbo quarry dust-exposed, and CTR for the control. Each was further subdivided into four subgroups (n = 6) corresponding to exposure durations of 3, 6, 9, and 12 months. Biochemical parameters including renal indices, cardiovascular biomarkers, and broncho-alveolar lavage (BAL) fluid markers were evaluated at the end of these periods. The results indicated duration-dependent elevations in serum creatinine, urea, uric acid, electrolytes, cardiac troponin I (cTnI), creatine kinase (CK), lactate dehydrogenase (LDH), total cholesterol (TC), low density lipoprotein (LDL) cholesterol, triacylglycerol (TAG), and BAL fluid LDH, alkaline phosphatase (ALP), and total protein, with corresponding reductions in high density lipoprotein (HDL)-cholesterol. Toxic effects were consistently more severe in AMN animals. These findings demonstrate that prolonged quarry dust exposure induces progressive multi-organ toxicity which could be attributed to oxidative stress, inflammation, toxic metal accumulation and particulate matter-induced mechanical stress in tissues. These findings indicate a significant occupational health risk associated with working in a quarry sites.

Keywords:

Quarry dust,
Toxic metals,
Renal injury,
Cardiovascular
Biomarkers,
BAL fluid

INTRODUCTION

Low availability of natural construction stones, coupled with environmental restrictions on river sand exploitation, positioned quarries and their products (chippings, quarry sand, etc.) as alternatives for use in the construction industry. However, the health implications of exposure to quarry dust from quarrying activities have not been adequately examined. Quarry dust is generated during excavation, crushing, and processing of rocks in quarries and it is an airborne particulate matter which can easily be inhaled. It usually contains crystalline silica, heavy metal, metallic oxides etc., depending on the type of parent rock (Orinya *et al.*, 2025).

These constituents, especially heavy metals pose serious occupational and environmental health risks (Ogbeide and Ogbeide, 2026; Obasi *et al.*, 2017).

In quarry industries, the major activities include blasting, transport, crushing, sieving and loading. Significant quantity of dust is emitted in all these processes, and the consequences become more pronounced in the developing countries like Nigeria where little or no dust control measures exist. The particle size of quarry dust varies a lot depending on the type of rock, driller, blaster, crusher, hauler and sieve. However, inhalable particles are $\leq 100 \mu\text{m}$, but health-relevant fractions are classified by aerodynamic diameter and deposition site after inhalation.

The thoracic fraction (PM₁₀) is $\leq 10 \mu\text{m}$ and penetrates beyond the larynx into the tracheobronchial region (Nguyen *et al.*, 2022), while the respirable fraction (PM₄) is $\leq 4 \mu\text{m}$ and reaches the alveolar/gas-exchange area (Sirianni *et al.*, 2020). PM_{2.5}, the fine particulate matter is $\leq 2.5 \mu\text{m}$, and PM_{0.1}, the ultrafine particles is $\leq 0.1 \mu\text{m}$. They are capable of alveolar deposition, leading to pulmonary toxicity, or subsequently enter the blood stream and transported to other parts of the body where they cause systemic injury and toxicities in different parts of the body via oxidative stress and inflammatory mediators (Kelly and Fussell, 2020; Bowe *et al.*, 2018). In Nigeria, one of the significant sources of environmental pollutants is quarry industry (Unuraye, 2005). In Ebonyi state particularly, enormous quantity of quarry dust is released into the environment daily by multitude of quarry industries domiciled in the state. Furthermore, most employees of these industries work manually without proper personal protection equipment, which directly exposed them to the dust for a long period. Complicating the matter is that most of the workers do not have adequate knowledge on the health implications of long-term quarry dust exposure. High rate of unemployment without an efficient welfare package for the less privileged forces the unskilled poor, especially local community members to find a means of livelihood in menial jobs like labourers in quarry sites.

Research have shown that prolonged occupational exposure to quarry dust restrictive and obstructive lung diseases, progressive declines in pulmonary function, and increased respiratory symptoms among quarry workers across diverse geographic settings (Ike-Samuel *et al.*, 2025). Beyond respiratory toxicity, other research reported that prolonged exposure to quarry dust can exert some systemic effects (Orinya *et al.*, 2024). Occupational studies found that quarry workers had elevated levels of

serum creatinine, urea, and uric acid, suggesting progressive kidney impairment which may be due to cellular oxidative damage caused by prolonged accumulation of toxicants from inhaled quarry dust (Aloh *et al.*, 2024). Other conditions, such as high blood pressure and altered cardiovascular parameters, have also been documented in populations exposed. (Li *et al.*, 2025).

In many African countries like Nigeria, people are conservative in volunteering information for research purposes and may sometimes be hesitant and difficult in making themselves available for screening. Therefore, this study employed an animal-based randomized controlled design to evaluate the renal, cardiovascular, lipid profile and pulmonary effects of chronic exposure to quarry dust at two quarry communities in Ebonyi state, providing insights into organ-specific toxicological consequences.

MATERIALS AND METHODS

Study Design

The study employed an animal-based randomized controlled experimental design to evaluate the biochemical changes in the heart, kidneys, and lungs of guinea pigs exposed to quarry dust at Umuoghara and Amoffia-Ngbo quarry sites in Ebonyi State, Nigeria.

Study area

The two quarry sites are located at Umuoghara (umr) community in Ezza North Local Government Area, and Ammoffia Ngbo (amn) community in Ohaukwu Local Government Area, while the control (ctr) is at CAS Campus of Ebonyi State University about 10km and 20km from the two quarry sites respectively. The geographical coordinates are (6°18'N and 8°2'E), (6°22'N and 8°9'E) and (6°19'N and 8°4'E) respectively.

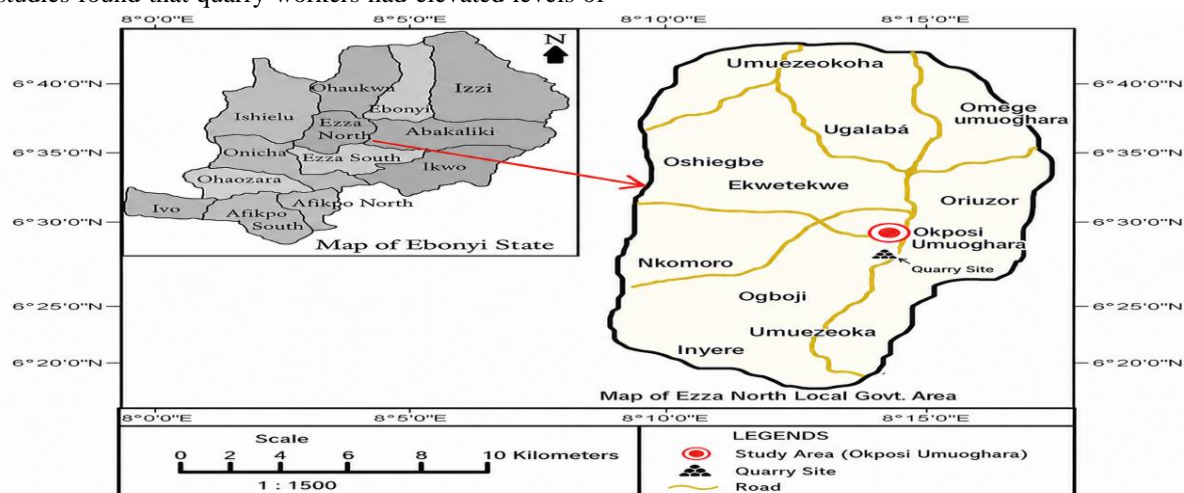


Fig 1. A map of Ezza North Local government Area showing the Study Area (Source: Modified after <https://www.nierigalleria.com/Nigeria/statesNigeria/Images/Ebonyi-State-Political-Map-jpg>)

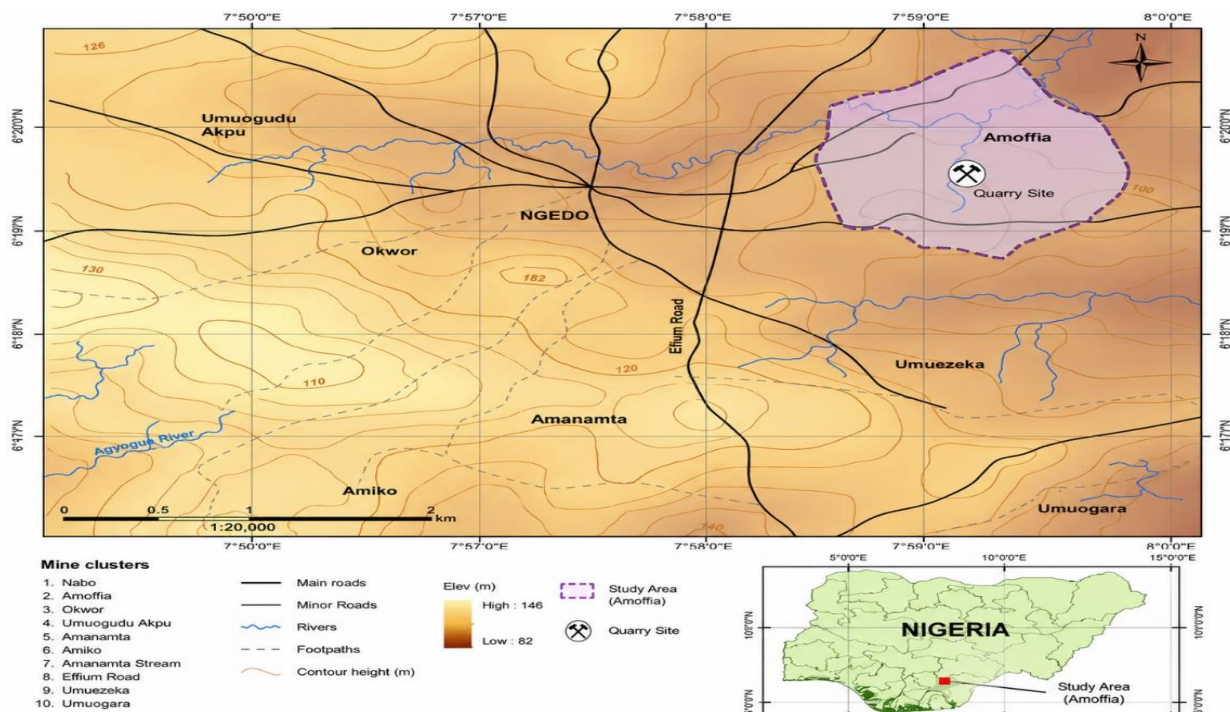


Fig 2. A Map Showing Amoffia Ngbo Study Area (sources: Ene *et al.*, 2024 modified).

Experimental Animals and Grouping

Seventy-two (72) male guinea pigs weighing 800 -1200 g were randomly assigned into three groups (24 per group): Umuoghara quarry dust-exposed (UMR), Amoffia-Ngbo quarry dust-exposed (AMN), and control. Each was further subdivided into four subgroups (n = 6) corresponding to exposure durations of 3, 6, 9, and 12 months.

Exposure of Animals to quarry dust

The experimental animals were exposed to quarry dust emanating directly from quarrying activities at the study sites. The exposure time was maintained with the working hours (8am to 6pm), after which the animals were taken to a house free from the quarry dust and transferred to a clean cage on daily basis till the end of exposure period. Control animals were housed at the College of Agriculture Campus, Ebonyi State University which is free from quarry dust. Animals had ad libitum access to feed and water.

Assessment of Renal Function Indices

The levels of serum creatinine (Jaffe's method), urea (Berthelot method), uric acid (uricase-peroxidase method), and electrolytes (Na^+ , K^+ , Cl^-) were determined using standard spectrophotometric procedures as previously described (Bartels *et al.*, 1972; Fawcett and Scott, 1960; Fossati *et al.*, 1980; Henry *et al.*, 1974).

Cardiovascular Biomarkers and Lipid Profile

The activities of creatine kinase (Steen *et al.*, 2010), lactate dehydrogenase (Tietz, 1987), and levels of cardiac troponin I (Etievent *et al.*, 1995) were measured using enzymatic and ELISA-based methods. The levels of total cholesterol, HDL-cholesterol, LDL-cholesterol, and triglycerides were analyzed using enzymatic colorimetric assays (Tietz, 1990).

Pulmonary Lavage Analysis

Bronchoalveolar lavage (BAL) fluids were collected using phosphate-buffered saline as described by Leo *et al.* (1989). BAL fluid LDH activities, alkaline phosphatase (ALP) activities, and total protein were determined using standard enzymatic procedures.

Statistical Analysis

Data obtained were statistically analyzed with two-way ANOVA and turkey multi comparison test done with Graphpad prism software (version 6.0). Values at $p < 0.05$ were considered to be statistically significant.

RESULTS AND DISCUSSION

Effects of Quarry Dust Exposure on Renal Function Indices of Guinea Pigs

Figures 3-8 show the renal function indices of the different groups of guinea pigs. The levels of serum creatinine, urea, uric acid, and serum electrolytes (Na^+ , K^+ , and Cl^-) of guinea pigs exposed in both quarry sites were significantly ($p < 0.05$) higher than the levels in

serum of the control, and were observed to increase with length of exposure. Creatinine, urea, uric acid, and the serum electrolytes levels were observed to be

significantly ($p < 0.05$) higher in serum of AMN guinea pigs when compared to UMR guinea pigs.

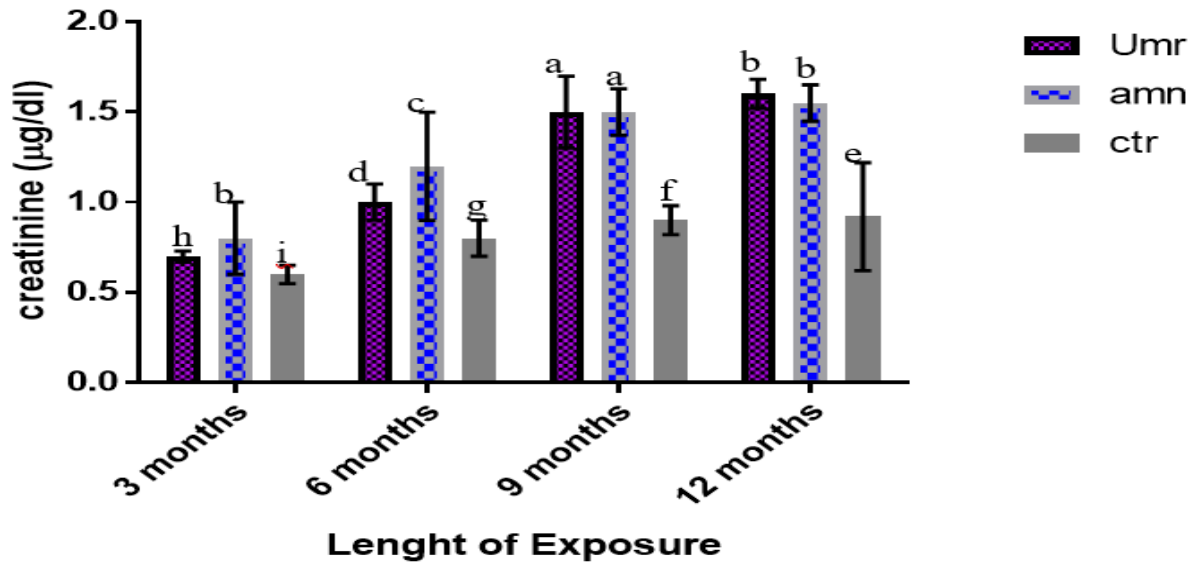


Fig 3. Levels of creatinine in serum of the different groups of guinea pigs

The data are expressed as mean \pm SD (n=6) and significant difference at $p < 0.05$. Umr = Umuoghara

quarry dust-exposed groups, amn = Amoffia Ngbo quarry dust-exposed groups, ctr = Control site groups. *Bars in a group with the same letter are not significantly different

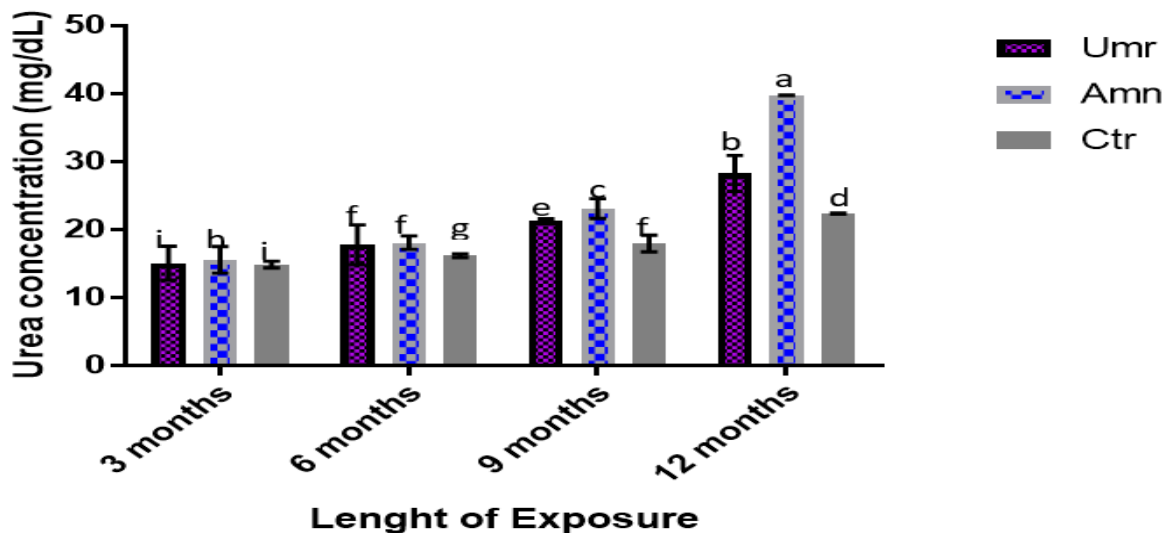


Fig 4. Levels of Urea in serum of the different groups of guinea pigs

The data are expressed as mean \pm SD (n=6) and significant difference at $p < 0.05$. Umr = Umuoghara quarry dust-exposed groups, Amn = Amoffia Ngbo

quarry dust-exposed groups, Ctr = Control site groups. *Bars in a group with the same letter are not significantly

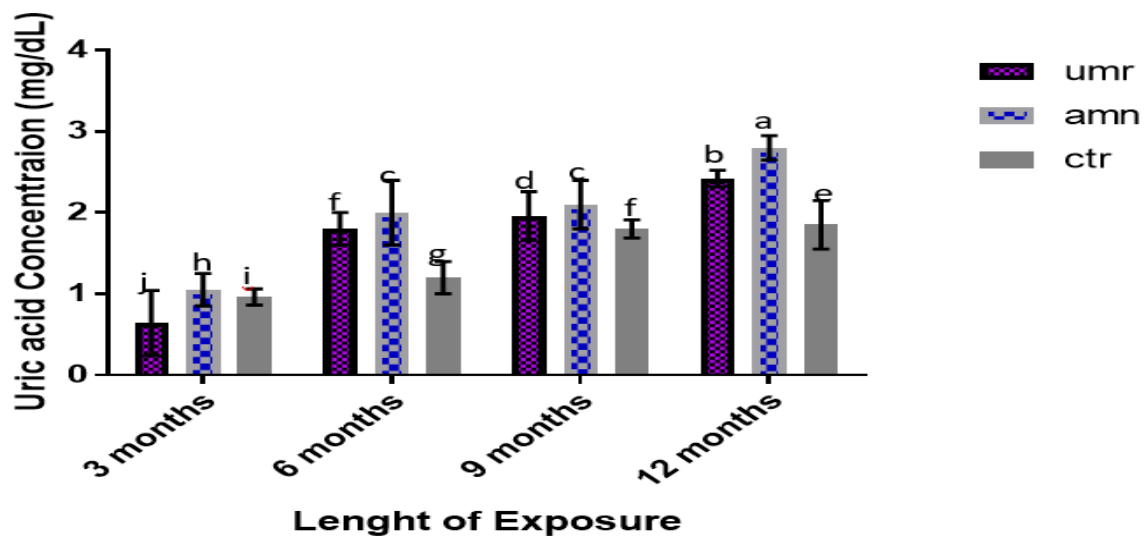


Fig 5. Uric acid levels in serum of the different groups of guinea pigs

The data are expressed as mean \pm SD (n=6) and dust-exposed groups, ctr = Control site groups. *Bars in significant difference at $p < 0.05$. umr = Umuoghara quarry dust-exposed groups, amn = Amoffia Ngbo quarry a group with the same letter are not significantly different

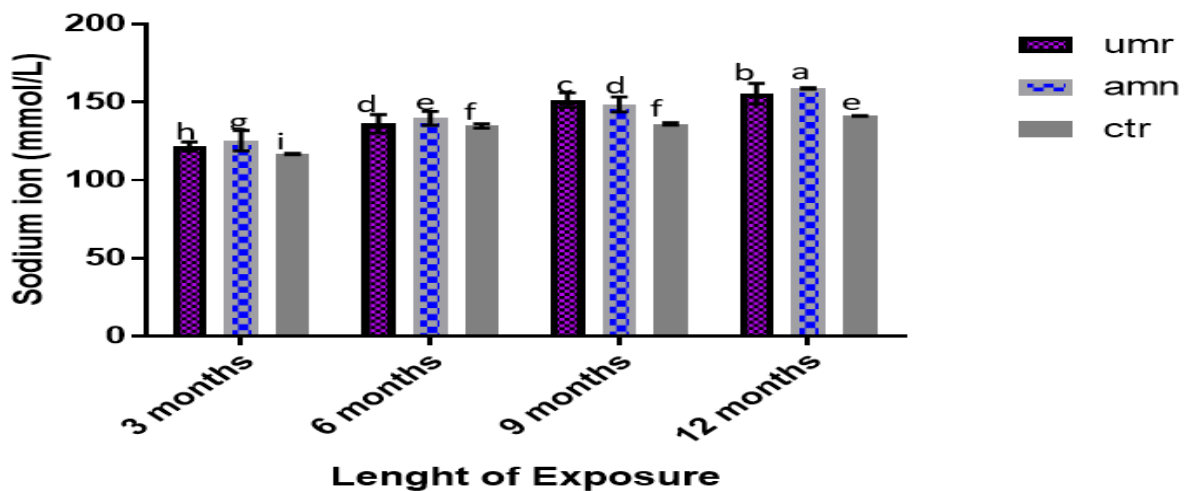


Fig 6. Levels of Na⁺ in serum of the different groups of guinea pigs

The data are expressed as mean \pm SD (n=6) and dust-exposed groups, ctr = Control site groups. *Bars in significant difference at $p < 0.05$. umr = Umuoghara quarry dust-exposed groups, amn = Amoffia Ngbo quarry a group with the same letter are not significantly different

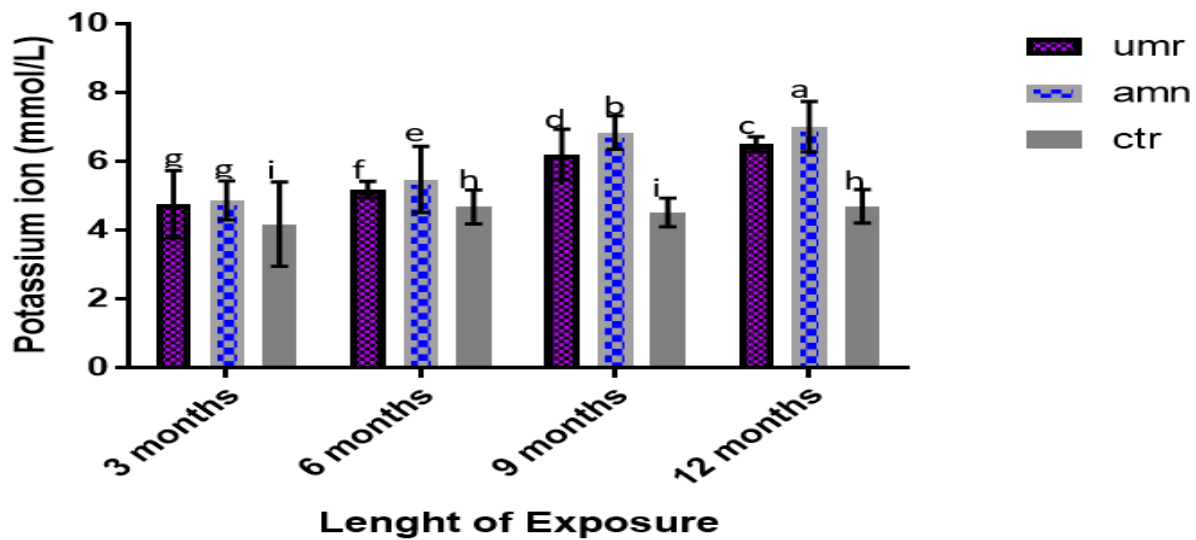


Figure 7: Levels of K⁺ in serum of the different groups of guinea pigs

The data are expressed as mean \pm SD (n=6) and significant difference at $p < 0.05$. umr = Umuoghara quarry dust-exposed groups, amn = Amoffia Ngbo quarry dust-exposed groups, ctr = Control site groups. *Bars in a group with the same letter are not significantly different

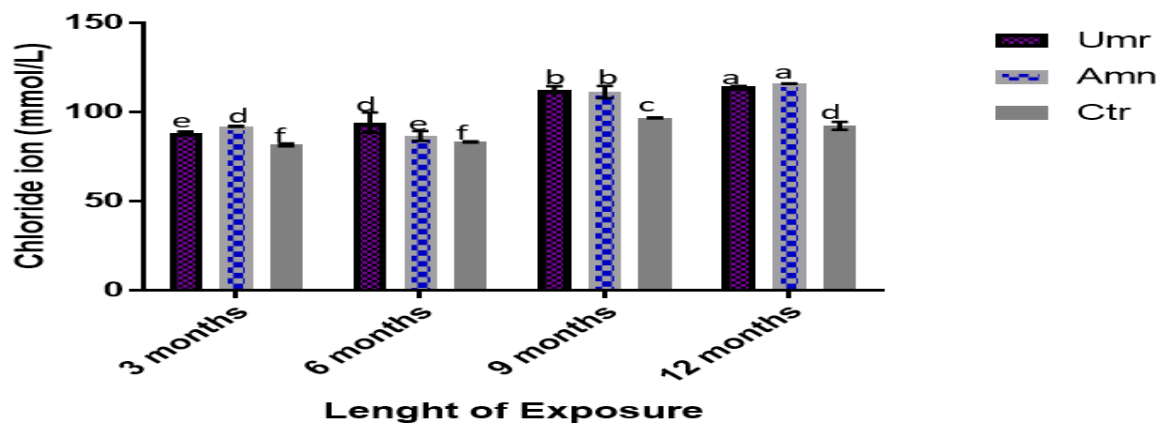


Fig 8. Levels of Cl⁻ in Serum of the different groups of guinea pigs

The data are expressed as mean \pm SD (n=6) and significant difference at $p < 0.05$. Umr = Umuoghara quarry dust-exposed groups, Amn = Amoffia Ngbo quarry dust-exposed groups, Ctr = Control site groups. *Bars in a group with the same letter are not significantly different

Effects Quarry Dust Exposure on Cardiovascular Parameters of Guinea Pigs

Figures 9 to 15 show the cardiovascular indices of the different groups of guinea pigs after exposure to quarry dust. Serum concentration of cTnI, and the activities of LDH and CK of guinea pigs exposed to quarry dusts were significantly ($p < 0.05$) higher than those of the control

groups and increased significantly ($p < 0.05$) with length of exposure. Levels of serum TC, LDL-cholesterol and TAG were significantly ($p < 0.05$) higher in the 6, 9 and 12 months-exposed guinea pigs compared to the controls, and also increased with duration of exposure. However, the levels of total cholesterol and TAG in 3 months-exposed groups at both sites were not significantly ($p > 0.05$) different from the levels in control groups. Additionally, the HDL-cholesterol levels recorded were significantly ($p < 0.05$) lower in serum of the dust-exposed animals than in the serum of the control groups with the exception of the 3 months-exposed group. The enzyme activities, TAG and LDL-cholesterol were

significantly higher in AMN guinea pigs compared to UMR guinea pigs.

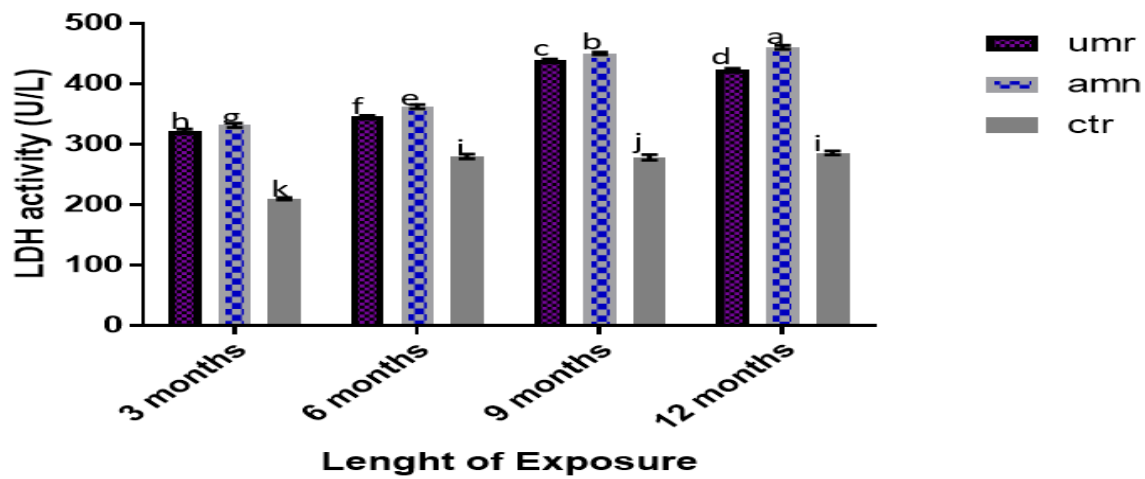


Fig 9. Lactate dehydrogenase (LDH) activities in Serum of the different groups of guinea pigs

The data are expressed as mean \pm SD (n=6) and significant difference at $p < 0.05$. umr = Umuoghara quarry dust-exposed groups, amn = A Moffia Ngbo quarry dust-exposed groups, ctr = Control site groups. *Bars in a group with the same letter are not significantly different

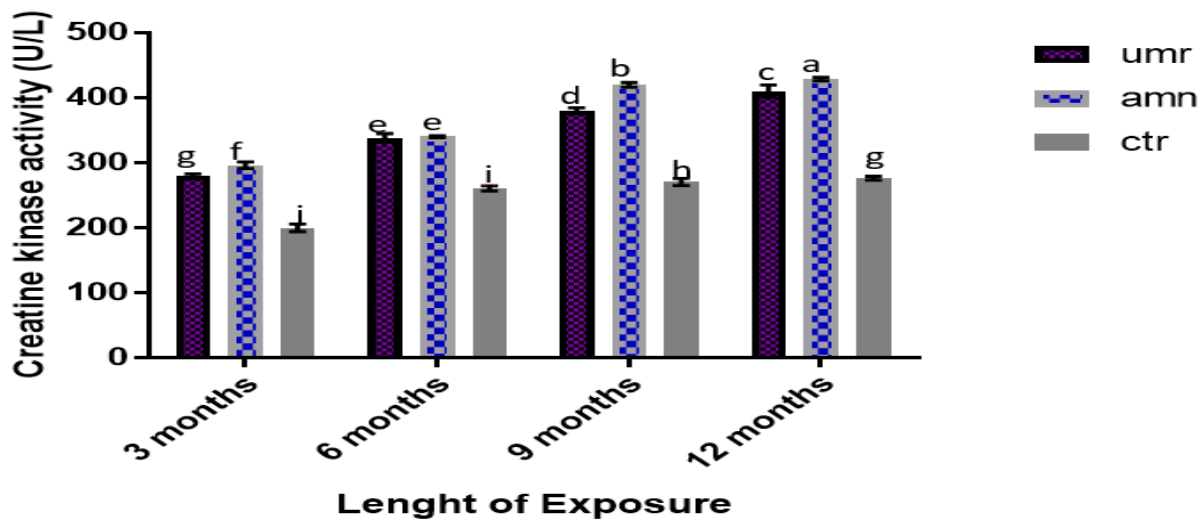


Fig 10. Creatine kinase (CK) activities in Serum of the different groups of guinea pigs

The data are expressed as mean \pm SD (n=6) and significant difference at $p < 0.05$. umr = Umuoghara quarry dust-exposed groups, amn = A Moffia Ngbo quarry dust-exposed groups, ctr = Control site groups. *Bars in a group with the same letter are not significantly different

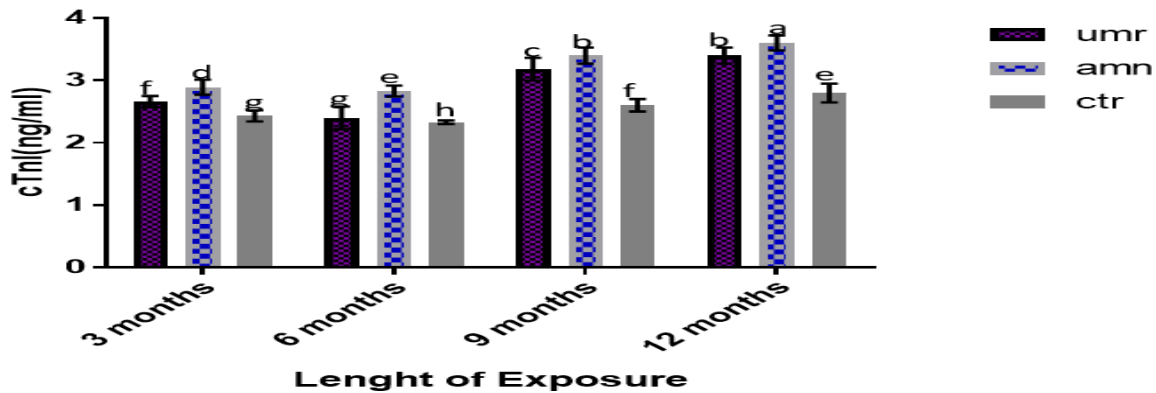


Fig 11. Cardiac troponin I levels (cTnI) in serum of different groups of the guinea pigs

The data are expressed as mean \pm SD (n=6) and significant difference at $p < 0.05$. umr = Umuoghara quarry dust-exposed groups, amn = A Moffia Ngbo quarry dust-exposed groups, ctr = Control site groups. *Bars in a group with the same letter are not significantly different

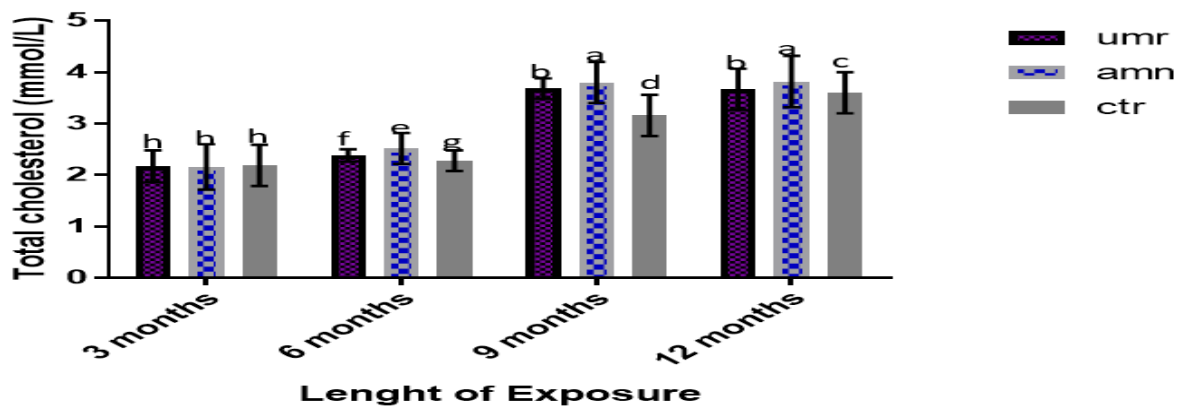


Fig 12. Total cholesterol levels in serum of the different groups of guinea pigs

The data are expressed as mean \pm SD (n=6) and significant difference at $p < 0.05$. umr = Umuoghara quarry dust-exposed groups, amn = A Moffia Ngbo quarry dust-exposed groups, ctr = Control site groups. *Bars in a group with the same letter are not significantly different

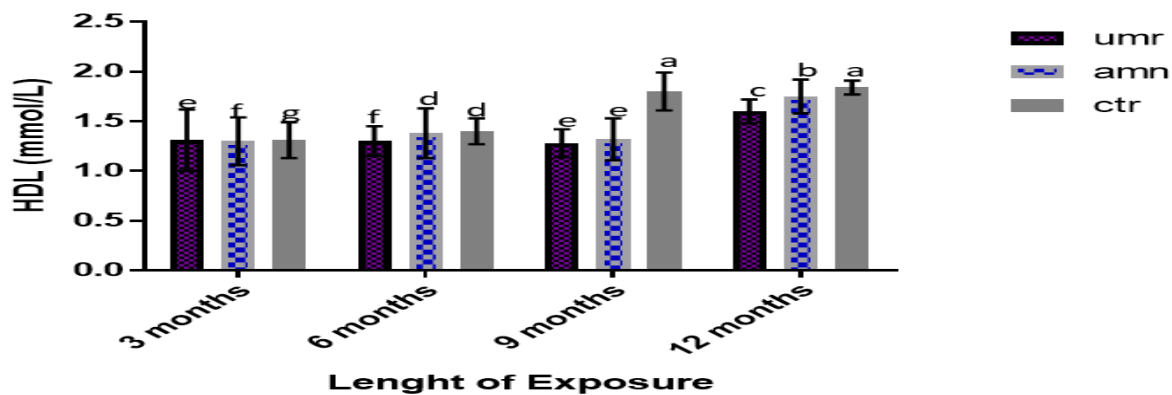


Fig 13. High density lipoprotein-cholesterol levels in serum in whole blood of the different groups of guinea pigs

The data are expressed as mean \pm SD (n=6) and significant difference at $p < 0.05$. umr = Umuoghara

quarry dust-exposed groups, amn = Amoffia Ngbo quarry dust-exposed groups, ctr = Control site groups. *Bars in a group with the same letter are not significantly different

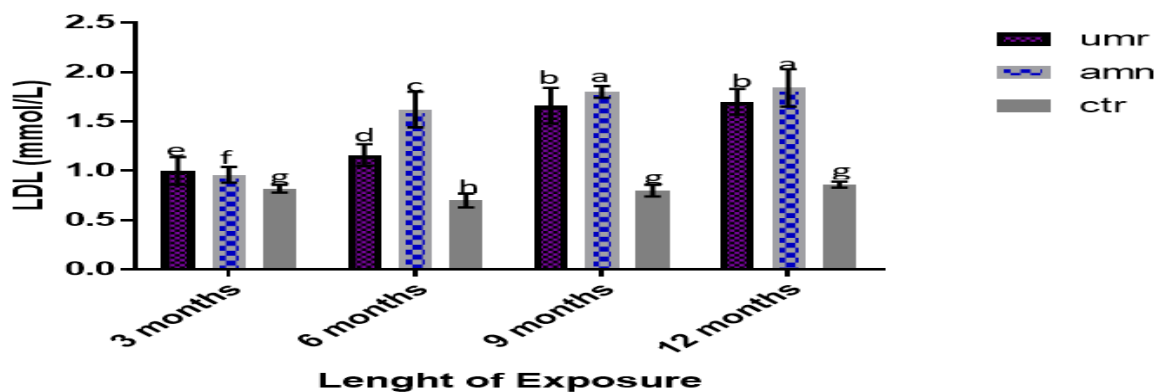


Fig 14. Levels of low density lipoprotein - cholesterol in serum of the different groups of guinea pigs

The data are expressed as mean \pm SD (n=6) and significant difference at $p < 0.05$. umr = Umuoghara quarry dust-exposed groups, amn = Amoffia Ngbo quarry

dust-exposed groups, ctr = Control site groups. *Bars in a group with the same letter are not significantly different

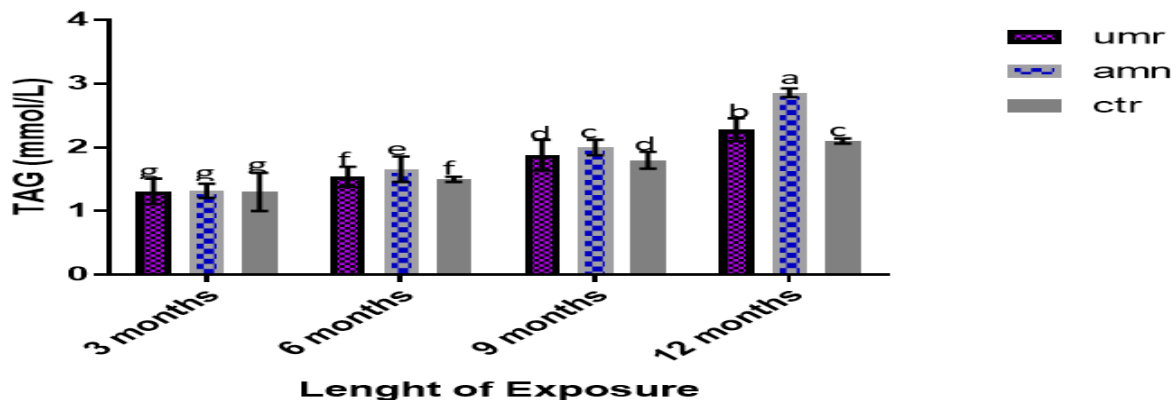


Fig 15. Triacylglycerides levels in serum of the different groups of guinea pigs

The data are expressed as mean \pm SD (n=6) and significant difference at $p < 0.05$. umr = Umuoghara quarry dust-exposed groups, amn = Amoffia Ngbo quarry dust-exposed groups, ctr = Control site groups. *Bars in a group with the same letter are not significantly different

Figures 16, 17 and 18 show the results of the pulmonary lavage indices of the different groups of the experimental animals. From the result, the activities of ALP and LDH, and total protein concentration in the lavage fluid of the guinea pigs exposed to quarry dust were significantly ($p < 0.05$) higher than those of the control and also increased significantly ($p < 0.05$) with duration exposure. These parameters were also observed to have a significant ($p < 0.05$) decrease in UMR guinea pigs when compared to AMN guinea pigs.

Effect of Quarry Dust Exposure on Pulmonary Lavage Parameters of Different Groups of Guinea Pigs

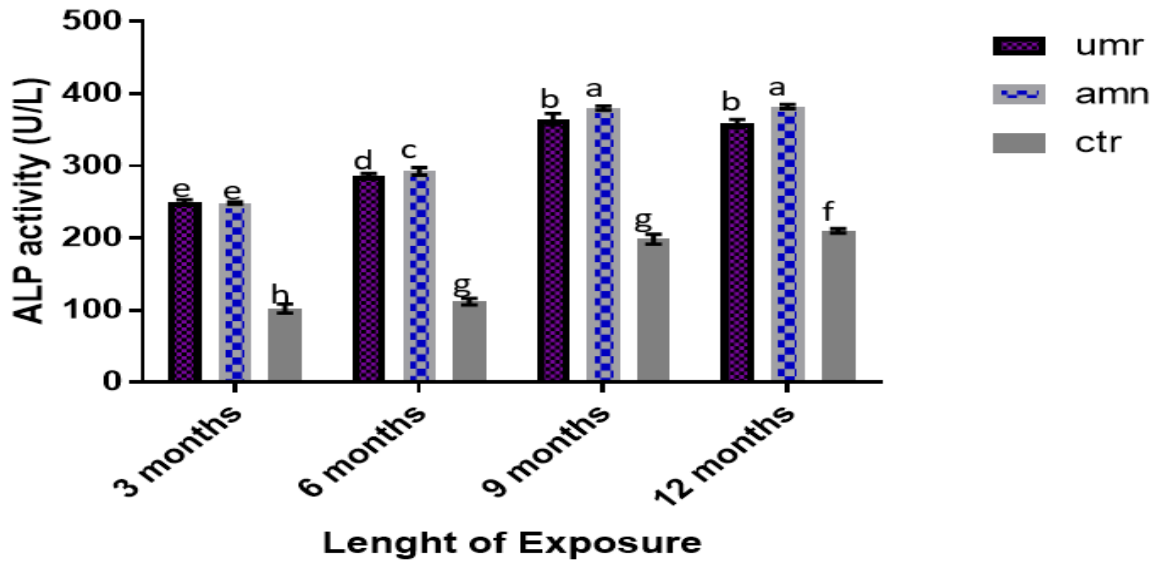


Fig 16. ALP activities in pulmonary lavage fluid of guinea pigs exposed to 'UMR' and 'AMN' quarry dust. The data are expressed as mean \pm SD (n=6) and significant difference at $p < 0.05$. umr = Umuoghara quarry dust-exposed groups, amn = Amoffia Ngbo quarry dust-exposed groups, ctr = Control site groups. *Bars in a group with the same letter are not significantly different

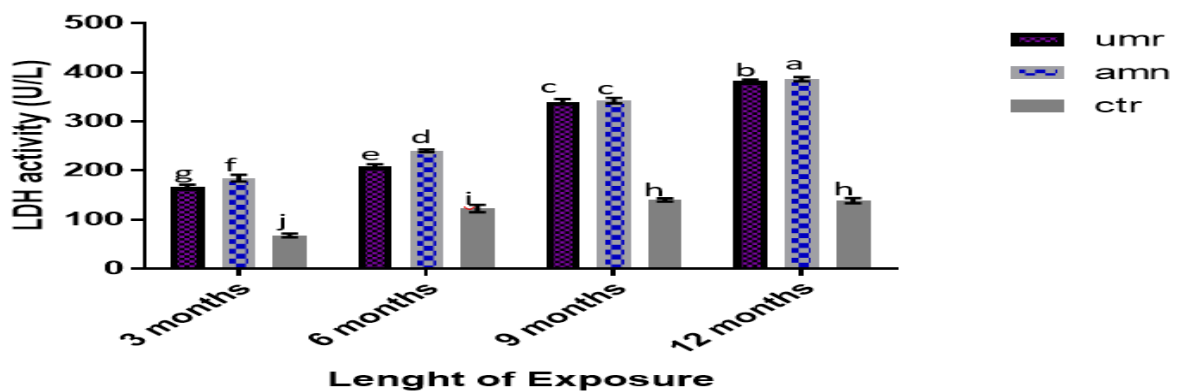


Fig 17. Lactate dehydrogenase activities in pulmonary lavage the different groups of guinea pigs The data are expressed as mean \pm SD (n=6) and significant difference at $p < 0.05$. umr = Umuoghara quarry dust-exposed groups, amn = Amoffia Ngbo quarry dust-exposed groups, ctr = Control site groups. *Bars in a group with the same letter are not significantly different

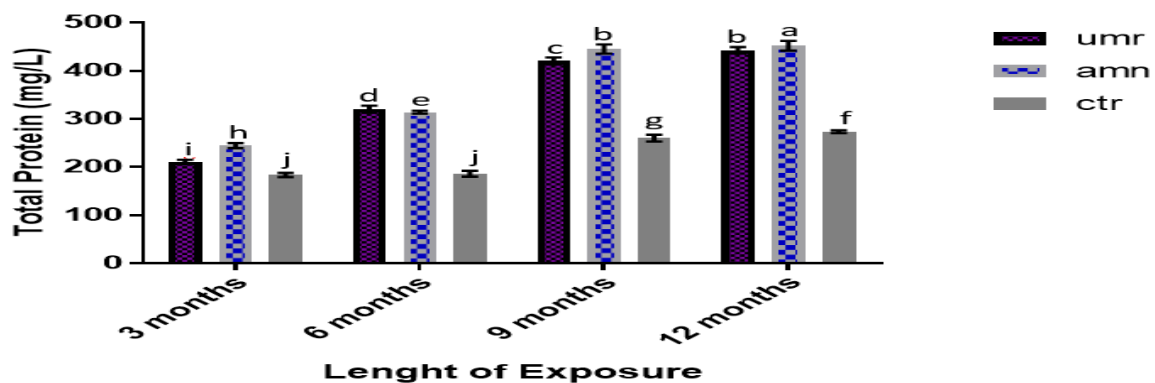
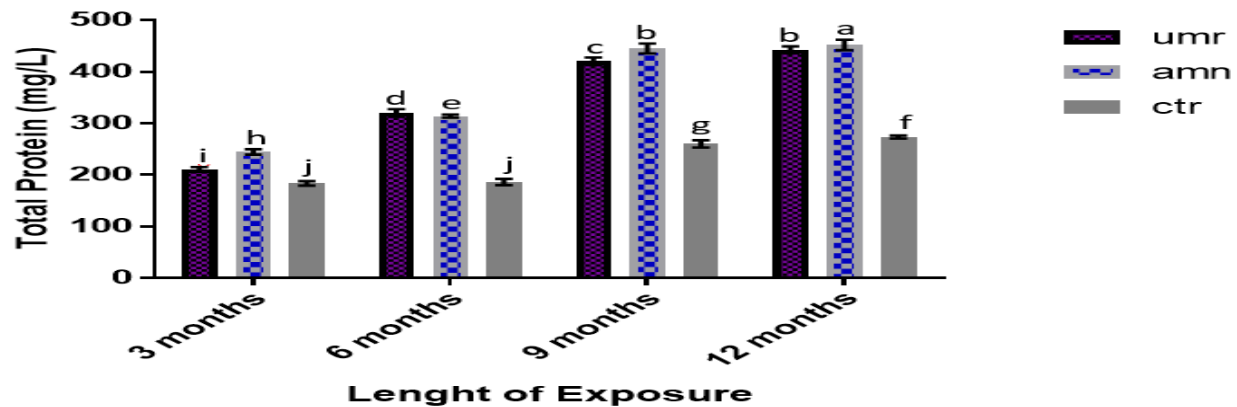


Fig 18. Levels of total protein in pulmonary lavage the different groups of guinea pigs

The data are expressed as mean \pm SD (n=6) and significant difference at $p < 0.05$. umr = Umuoghara quarry dust-exposed groups, amn = Amoffia Ngbo quarry

dust-exposed groups, ctr = Control site groups. *Bars in a group with the same letter are not significantly different

**Fig 18. Levels of total protein in pulmonary lavage the different groups of guinea pigs**

The data are expressed as mean \pm SD (n=6) and significant difference at $p < 0.05$. umr = Umuoghara quarry dust-exposed groups, amn = Amoffia Ngbo quarry dust-exposed groups, ctr = Control site groups. *Bars in a group with the same letter are not significantly different

parameters observed in quarry dust-exposed guinea pigs indicate impaired renal function, which may likely result from compromised glomerular filtration and tubular dysfunction (Kidney Disease: Improving Global Outcomes (KDIGO), 2024). These findings are in line with the reports of elevated concentrations of serum urea and creatinine among quarry workers, cement factory employees, and crush stone workers attributed to long-term occupational dust exposure (Adeosun *et al.*, 2025; Subramanian *et al.*, 2023).

The present study provides experimental evidence that chronic exposure to quarry dust from Umuoghara and Amoffia-Ngbo quarry sites in Ebonyi State induced progressive, multi-system toxicity in guinea pigs, with pronounced alterations in renal, cardiovascular, and pulmonary functions. These toxicological effects intensified with increasing duration of exposure and were consistently more severe in animals exposed at the Amoffia-Ngbo site, strongly suggesting that the severity of quarry dust toxicity is dependent not only on exposure duration, but also on site-specific differences in dust chemistry and particulate matter compositions of toxicants. The findings from this research align with growing experimental and epidemiological evidence linking long-term particulate matter exposure to oxidative stress mediated organ dysfunction and systemic inflammation. (Wathanavasin *et al.*, 2024).

The observed elevation in serum uric acid further portrays renal toxicity, as uric acid (the end oxidation product of purine catabolism) is excreted primarily by the kidneys. Decreased glomerular filtration rate is usually linked to hyperuricemia, and importantly, emerging evidence suggests that uric acid is not merely a marker but an active contributor to liver disorder (KDIGO, 2024). Sánchez-Lozada *et al.* (2005) reported that heightened level of uric acid induces thickening of afferent arterioles, which reduces renal blood flow and promotes ischemic nephropathy. The significant increase in creatinine, urea, and uric acid concentrations recorded in this study is suggestive of renal pathological condition caused by quarry dust-associated toxicants, and this is in line with reports of Bama *et al.* (2022).

Renal Function Alterations Following Quarry Dust Exposure

Measurements of creatinine, urea, uric acid, and electrolytes (Na^+ , K^+ , and Cl^-) levels are well-known indices of renal clearance, and their accumulation in serum is an indication of reduced nephron efficiency or altered renal perfusion (Trevisani *et al.*, 2020; Salgado *et al.*, 2024). The significant elevations in the levels of these

Toxic metals from particulate dust are known to preferentially accumulate in renal tissues because the kidneys have the capacity to reabsorb divalent metals. Prolonged inhalation of metal rich quarry dust induce oxidative stress, mitochondrial dysfunction, inflammatory signaling, and tubular necrosis, leading to nephropathies (Hou *et al.*, 2024). The significant renal dysfunctions seen in guinea pigs exposed to quarry dust

at Amoffia-Ngbo site compared to Umuoghara and control sites could be a result of higher particulate matter load of toxicants, including heavy metals at this particular site.

The observed electrolyte imbalance in this study further implicates the quarry dust constituents in renal dysregulation. The kidneys play a critical function in maintaining electrolyte homeostasis, including sodium and potassium balance, and this is controlled through aldosterone-mediated mechanisms and sodium-potassium ATPase activity (Palmer, 2015). In contrast to the works of Babalola and Babajide (2009) which reported an inverse Na^+/K^+ relationships in dust-exposed workers, the simultaneous elevation of Na^+ , K^+ , and Cl^- observed in this study suggests that chronic exposure may overwhelm compensatory renal mechanisms, leading to electrolyte retention and altered tubular function (Khan *et al.*, 2025).

Cardiovascular Toxicity Induced by Quarry Dust

Cardiac troponins, especially cTnI, are highly specific and sensitive biomarkers of myocardial injury (Xu *et al.*, 2025). Additionally, increase in the activities of LDH and CK in the serum are also key pointers to myocardial injury (Sakuragi *et al.*, 2024; Zhang *et al.*, 2024). The significant elevation in serum concentration of cTnI recorded in quarry dust-exposed guinea pigs is suggestive of myocardial injury and compromised cardiac function. The concordant elevations of LDH and CK further corroborate the presence of tissue and cellular injury, as these enzymes are released into circulation following cell disruption. These findings are in line with the report of elevated cardiac injury biomarkers among cement and quarry workers chronically exposed to dust (Bassey *et al.*, 2017). Persistent pulmonary injury has been associated with prolonged inhalation and accumulation of quarry dust, which may further result in pulmonary hypertension, systemic hypoxia, and secondary cardiac stress (Akinola *et al.*, 2008). Moreover, heavy metals such as cadmium and arsenic commonly found in quarry and cement dust can cause cardio-toxicity through oxidative stress, endothelial dysfunction, and mitochondrial injury, leading to elevated troponin levels and CK activities (Nazimabashir, 2015; Navas-Acien *et al.*, 2005).

The observed dyslipidemia among the quarry dust-exposed guinea pigs, evidenced by high levels of total cholesterol, LDL-cholesterol, and triglycerides followed by a decrease in HDL-cholesterol, further underscores the cardiovascular risk associated with quarry dust exposure. The observed exposure-duration dependent changes in exposed animals when compared to the control further supports the records on exposure chronic exposure to mineralogical dust and particulate matter (Mao *et al.*, 2017; Wang *et al.*, 2014; Zhang *et al.*, 2011).

The anomalous changes in lipid profile characterized by elevated levels of TC and LDL-cholesterol, and reduced

levels of HDL-cholesterol in experimental animals is an indication of the atherogenic potentials of prolonged exposure to quarry dust, and this is concordant with increased risk of cardiovascular damage associated with occupational exposure to particulate dust (Wang *et al.*, 2021). HDL-C mediates the efflux of cholesterol from peripheral tissues, inhibits LDL oxidation and exhibits anti-inflammatory activities, thus exerting anti-atherogenic capacity. Therefore, reduced level of this lipid will lead to atherogenesis and cardiac disorder (Rader and Tall, 2012). The dislipidaemia observed in this work could be strongly attributed to the heavy metals and other toxicants present in the quarry dust. Heavy metals are known to promote lipid peroxidation and disrupt lipid metabolism in part by increasing the activity of HMG-CoA reductase (the rate-limiting enzyme in the pathway of cholesterol synthesis) and by depleting antioxidant reserves that protects the body from reactive oxygen species and oxidative damage (Valko *et al.*, 2005). Additionally, lead toxicity has also been associated with the impairment of the expression of LDL receptors, thereby inhibiting cholesterol clearance (Liu *et al.*, 2011). Transition metals has been found in quarry dusts and are capable of catalyzing Fenton reactions which can generate reactive oxygen species, directly promoting LDL oxidation and vascular inflammation (Donaldson *et al.*, 2001). The significant increase in TAG in the experimental animals further substantiates the cardiovascular risk of the quarry dust exposure because hypertriglyceridaemia promotes formation of small, dense LDL particles that are more susceptible to oxidation and impairs HDL maturation and function (Chapman *et al.*, 2011). All these suggests that the quarry dust exposure was associated with increased cardiovascular disease risk.

Pulmonary Inflammatory Response to Quarry Dust Exposure

Elevated LDH and ALP in BAL fluid is a recognized indicator of pulmonary cell injury and cytotoxicity, while increased total protein indicates enhanced alveolar-capillary barrier permeability and leakage of plasma proteins into the alveolar space (Labus *et al.*, 2022). Additionally, Particulate matter contents like crystalline silica and heavy metals are engulfed by alveolar macrophages and epithelial cells but cannot be digested. This can cause “frustrated phagocytosis,” lysosomal rupture, release of cathepsins and reactive oxygen species (ROS). The ROS coupled with the mechanical stress can cause membrane lipid peroxidation and necrosis, leading to leakage of LDH and ALP into the alveolar space (Kawano-Dourado *et al.*, 2018). The significant increases in LDH and ALP activities, as well as the levels of total protein in BAL fluids of quarry dust-exposed guinea pigs indicates pulmonary toxicity. These parameters were significantly higher in animals exposed at the Amoffia-Ngbo site, indicating that the pulmonary toxicant is

higher in the dust at this quarry site. The findings are consistent with studies that reported increased BAL fluid LDH and ALP activities, and protein levels, following exposure to silica, ultrafine particles, and ambient particulate matter (Li *et al.*, 2020; Zhou *et al.*, 2023). The consistent increase in the activities these enzymes may be suggestive of epithelial injury and sustained inflammatory response, likely driven by particle deposition, metal contamination, and oxidative stress. Pulmonary inflammation is a typical response to inhaled particulates and it has been strongly associated with chronic pathological outcomes such as fibrosis, emphysema, and carcinogenesis resulting from chronic inhalation and deposition of dust particles in the pulmonary tract (Johansson *et al.*, 2014; Sese *et al.*, 2018; Swanton, 2022). Consequently, pulmonary inflammation may also trigger systemic spill-over effects, leading to kidney damage and cardiovascular injury via circulating inflammatory mediators and oxidative pathways (Kelly and Fussell, 2020; Li *et al.*, 2023).

Site-Specific Differences and Toxicological Implications

Across renal, cardiovascular, and pulmonary markers of toxicity, guinea pigs exposed at the Amoffia-Ngbo quarry site consistently exhibited more severe biochemical and organ aberration than those exposed at Umuogbara. This observation aligns with earlier findings of higher particulate matter load and metal concentrations at the Amoffia-Ngbo site (Orinya *et al.*, 2024). This underscores the importance of dust composition and metal content, rather than exposure duration alone, in determining toxicological outcomes occupational exposure to dust.

CONCLUSION

This study is a demonstration of the fact that long-term exposure to quarry dust can induce significant, progressive, and multi-organ toxicity in guinea pigs, mediated largely by oxidative stress, inflammatory signaling, and heavy metal bioaccumulation. The renal dysfunction, myocardial injury, dyslipidemia, and pulmonary inflammation observed in this study has provided strong experimental support for epidemiological observations among quarry and cement workers. These findings highlight the urgent need for effective dust control measures, routine occupational health surveillance, and stricter regulatory enforcement to mitigate the health risks associated with quarrying activities.

Conflict of Interest.

The authors declare no conflict of interest with respect to this research.

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