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Modeling Lead Mobility in Soil: A Case Study of Lead Mining Activities in TungaTsauni, Gurara, Niger State, Nigeria

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Abstract

There areserious concerns about the recent reports of lead poisoning in some parts of Nigeria. The identification of lead mining activities at TungaTsauni, Gurara Local Government Area of Niger State, Nigeriahas actually necessitated this research in order to obtain a tool that can be used to predict the movement of lead in the soilsof the area. As such, two mathematical models have been developed – one using the convection-dispersion transport approach and the other using the simplified model suggested by Tolessa (2004).It was discovered from the results obtained, after the simulations of the model equations with the aid of MathCAd 14, that the concentration of lead in soil at different positions, which indicates its mobility, could be better represented using the model presented by Tolessa (2004)than using the one developed from the convection-dispersion transport approach because the correlation coefficient values obtained when the model suggested by Tolessa (2004) was modeled and simulated for the system considered in this work and compared to the experimental ones were 0.990525, 0.985546, 0.989689 and 0.988302, while those of the convection-dispersion transport approach were -0.67788, -0.71531, -0.70267 and -0.6053, respectively along the North, the South, the West and the East cardinal directions. As such, Equation (5) has been discovered to be a good tool to be used in truly representing the phenomenon of lead metal mobility in the soil of TungaTsauni, Gurara Local Government Area of Niger State, Nigeria. In addition, the developed model Equation (5) is hoped to beapplicable in predicting the lead mobility in the soil so as to ascertain the safe areas for agricultural activities in Tunga Tsauni partof Niger State, Nigeria.

Keywords:Modeling, heavy metals, lead mobility, soil,Nigeria.

1.0 INTRODUCTION

Lead (Pb) has been known as a contaminant posing threats to both soil quality and human health (Hettiarachchi*et al.*, 2001) and classified by the United State Environmental Protection Agency (USEPA) as being potentially hazardous and toxic to most forms of life (Awofolu, 2005; Okoronkwo*et al.*, 2005). Lead is a biologically nonessential element, highly toxic to humans as well as animal development, and plant (Francis, 2005; Pan*et al.*, 2005). Lead pollution is a problem that cannot be neglected because it exists in many forms in natural sources and remains over long periods in soil with high toxicity levels, which affects crop production and has the potential hazard to human health problems (Gopal and Rizvi, 2008). Soil contamination with heavy metals has attracted interest, due to both environmental and health-risk concerns (Essa, 1999; Cui*et al.*, 2005; Alao*et al.*, 2010).

Several incidents of lead poisoning have also been reported in Nigeria, such as the case of lead poisoning reported in Zamfara State, where more than 100 children in the villages of Dareta and Yargalma were seriously affected with a mean blood lead concentration of 119 µg/dl (levels as low as 10 µg/dl are associated with impaired neurological development in young children). Moreover, lead concentrations in soil of more than 100,000 ppm were found in and around the habitations in the villages (Galadima and Garba, 2012).

Literature has revealed that soil is the major recipient of lead pollution from the mining activities (Mahram*et al.*, 2007) and possible transmissions of lead from contaminated soil to the plants grown on the polluted soil to the animals that consume such plants have been suggested (Onyedika and Nwosu, 2008). In the polluted soils, lead is either absorbed and/or bio-accumulated by plant and animal that may eventually become available for human consumption. A positive correlation between lead in soil and blood lead concentration have been established and researchers have reported that excessive amounts of lead in human body can cause hypertension and brain damage (Itana, 2002). The quantity of naturally occurring lead in soils has been reported to be less than 50 mg/kg, while lead contaminated surface soils may contain more than 11,000 mg/kg.

Uncontrolled mining activities in Nigeria have resulted in generation of numerous environmental hazards, enormous amount of wastes and different types of pollutants (Onyedika and Nwosu, 2008). These mining activities raised serious concerns on the state of the soil, quality of crop plants and water source within and around the mining and exploration sites (Tomov and Kouzmova, 2005). Poor government policy and lack of good-will to properly implement law on uncontrolled mining activities like that of lead is possibly the cause of life-threatening contamination that is being experienced within the immediate natural ecosystem in Nigeria (Warhate*et al.*, 2006).

Therefore, the focus of this study is to develop a predictive mathematical model for the mobility of lead metal in soilin order to estimate the extent of the possible negative impact of mining activities inTungaTsauni, Nigeria.

2.0 METHODS

2.1 Modeling of Heavy Metal (Lead) Mobility in Soil

2.1.1 Conceptualization of the modeling method

Processes occurring in soils can be understood with the aid of mathematical and computer modeling. A number of models which can quantitatively predict movements and sorption of heavy metals in soils have been reported by Dube*et al.*, 2001. However, due to lots of unanswered questions about the strong heterogeneous nature of soil matrix, studies on the determination of the chemical properties of soil and heavy metal interactions have not been completely dealt with (Dube*et al.*, 2001).

From the experimental data obtained for lead concentrations in soil samples at various locations with respect to the mining site, a mathematical representation (model) can be developed. Furthermore, the developed model can be used to predict the concentrations of lead in soil at various distances from the mining site. After the validation of the developed model, its level of correlation with the experimental results can be used to determine whether to use it to predict lead concentrations at distances that are not considered in the experimental study or not.

2.1.2 Mathematical modeling of lead mobility in soil

Yahya and Abdulfatai (2007) developed a mathematical expression that described the mobility of heavy metals in soil under the assumptions that:

- porous medium is homogeneous, isotropic, and saturated;
- there is one-dimensional, steady-state water flow;
- thereis no dispersion in the directions transverse to the flow direction.

According to their work, the transport of heavy metals in soils was reported to be governed by the convection-dispersion transport equation developed by Selim*et al.* (1990), which is given, in Equation (1), as:

$$\rho\frac{\partial s}{\partial t}+\Theta\frac{\partial c}{\partial t}=\Theta D\frac{\partial^2 c}{\partial x^2}-v\frac{\partial c}{\partial x}-Q \qquad 1$$

where *c* = solute concentration in the soil solution (mg/*L*), *s* = amount of solute retained per unit mass of the soil matrix (mg/kg), *D* =hydrodynamic dispersion coefficient (cm^2/day), *v* = Darcy's water flux (cm hr^{-1}), Θ = volumetric soil moisture content (cm^3 cm^{-3}), *ρ* = soil bulk density (g cm^{-3}), *t* = time (hr), *x* = soil depth (cm), Q = sink-source term, which accounts for irreversible reactions such as precipitation, dissolution, mineralization, and immobilization.

The solution of Equation (1)gave a final expression for *c* as:

$$c = e^{\left(\frac{\theta}{k_d\rho+k_s\rho+\theta}\right)t} - e^{\left(\frac{v}{D\theta}\right)x} \qquad 2$$

Though Darcy's flux, *v,* is not the actual velocity in a given porous media but just a discharge rate per unit cross-sectional area, it has a unit of velocity [L/t] (Igboekwe and Uhegbu, 2011). Thus, it was substituted with (L/t) where L represents distance from mining site (m) and t the time (hr), and Equation (2), therefore, became:

$$C = e^{\left(\frac{\theta}{k_d\rho+k_s\rho+\theta}\right)\frac{L}{v}} - e^{\left(\frac{v}{D\theta}\right)x} \qquad 3$$

Equation (3) is thus the model equation for the transport of dissolved chemicals (such as heavy metals) in soils.

2.1.3 Criticism of the physical transport model

The model equation (Equation (3)) developed, which is based on dispersion-convection-sorption equalizations, is one of the most well-known mathematical or physical transport models of different chemical pollutants in soil matrix that have been described in literatures (Cukrowska et al., 2001). However, these models were observed to have some defects (Dube*et al.*, 2001).For instance:

a) they required many parameters at the beginning of the modeling, making it a bit more complicated,
b) they are simply physical equalizations of transport inside soil profile without consideration of the interaction between the contamination and the soil matrix, and

c) themodels also contain some approximations and assumptions, which in a significant manner modify the descriptions of transport phenomena. In fact, the model form of Equation (1) is named equalization of confusion because of misunderstandings which it evokes in researchers (Dube *et al.,* 2001).

Consequentially, the results obtained on the basis of these models are not always in good agreements with the real measurements in the natural environment (Hinz and Selim, 1994).

2.1.4 Alternative approaches to modeling of mobility of heavy metals (e.g., lead) in soil

Possible modern approaches to the modeling of sorption and transport of heavy metals in soil include (Dube *et al.*, 2001):

a) chemometrics, and
b) application of artificial neural networks

In chemometrics, a researcher can simulate natural soil and behavior of heavy metals in leaching column experiments and then try to use some chemometrics method to describe the obtained results. The application of artificial neural networks to modeling sorption and migration in soil canalsobe used to predict reasonable data, but it is assumed then that the user is ignorant of the physiochemical processes occurring inside the soil (Dube *et al.*, 2001).

2.1.5 A simplified lead mobility model

Having discovered that there are associated bugs with the convection-dispersion transport Equation (1)reported in section 2.1.2 of this work, an alternative simplified model that requires less monitoring data to estimate is hereby presented as reported by Tolessa (2004). According to Tolessa (2004), the simplified model was developed on the assumption that:

- there is a steady-state condition,
- the principle of first-order kinetics holds,
- thedecay (decomposition) of a pollutant or heavy metal (such as lead) is proportional to the initial concentration of the pollutant and the factor of proportionality, the decay rate coefficient *k* (s^{-1}).

According toTolessa (2004), the mobility of heavy metal such as lead in soil was reported to be governed by the transport equation expressed as:

$$\frac{dC}{dt} = -kC \qquad 4$$

Solution of Equation (4)yielded an equation for the concentration of the pollutant (lead) at any distance *x* as (Tolessa, 2004):

$$C_x = C_0 e^{-k\frac{x}{v}} \qquad 5$$

Where $C_x$is the concentration of the contaminant at distance *x* (mg/kg), C_0 is the initial concentration of the pollutant (mg/kg), *x* is the distance from the source of contamination (m), *v* is the average flow velocity (m/hr).Therefore, for the present study, the developed Equation (5) was used to simulate the mobility of lead in the soil present in the mining site considered in this work.

3.0 RESULTS AND DISCUSSIONS

3.1 Modeling of Lead Mobility in Soil

Mathematical models were developed to describe the mobility of lead metal in the soil (in terms of concentration) around the vicinity of the mining activities. Two separate models (Equations (3) and (5)) were developed and simulated. The models were simulated with the aid ofMathCAD 14 (PTC, 2007) and the obtained experimental data were used to test their validitiesas well as to predict the concentrations of lead in the soil at different distances from the mining site. After the validation and the selection of one of the developed models, its level of correlation with the experimental results was determined to know whether it can be used to predict lead concentrations at distances that were not considered in the experimental studies.

Figures 1-2 compared both the experimental results and the ones obtained from the simulation of the developed model Equation (3).

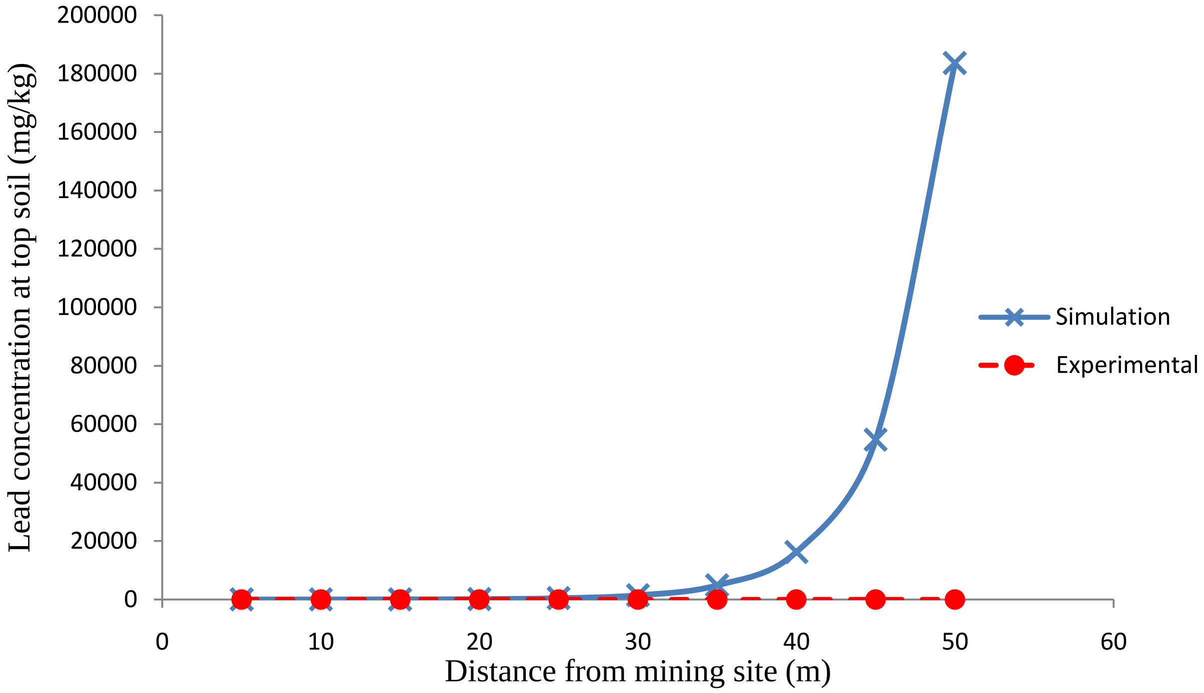

Figure 1. Lead concentrations in top-soil at various distances from mining site: North cardinal direction (from the results of Equation (3)).

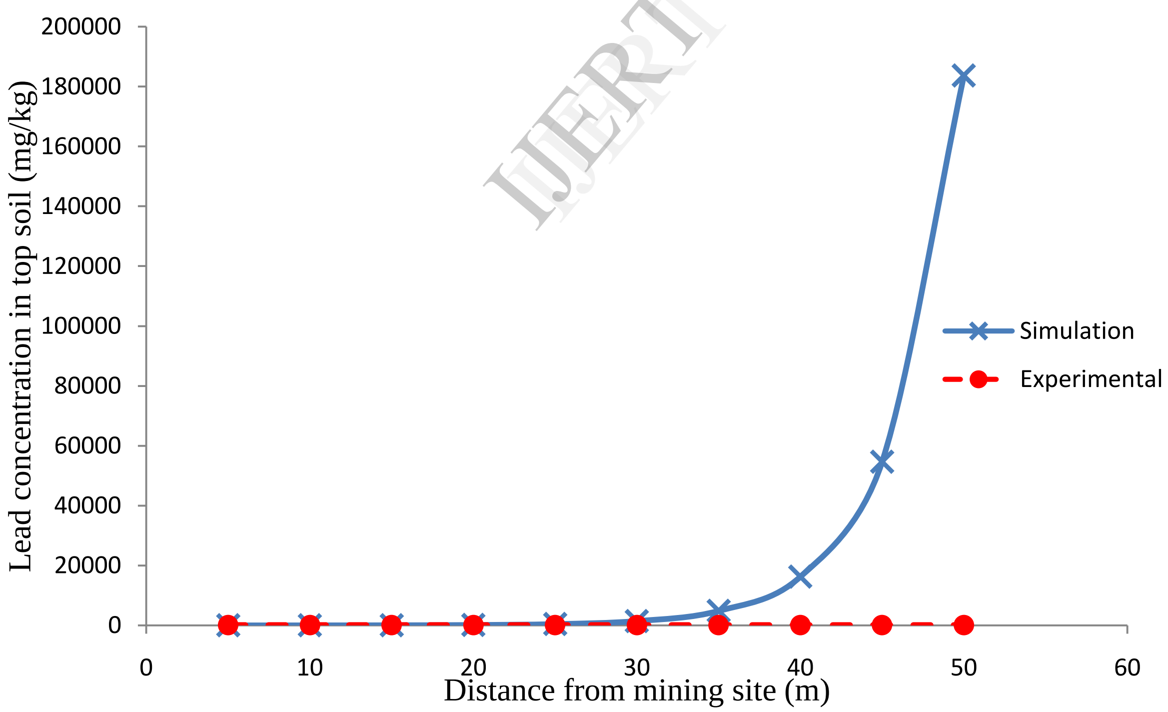

Figure 2.Lead concentrations in top-soil at various distances from mining site: South cardinal direction (from the results of Equation (3)).

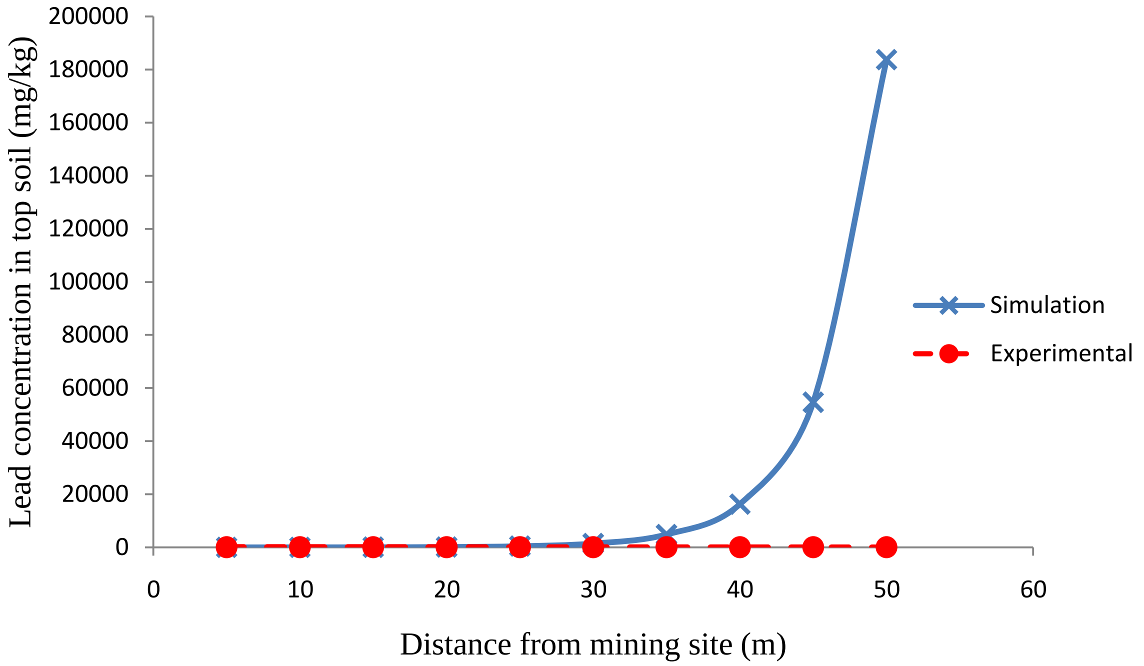

Figure 3.Lead concentrations in top-soil at various distances from mining site: West cardinal direction (from the results of Equation (3)).

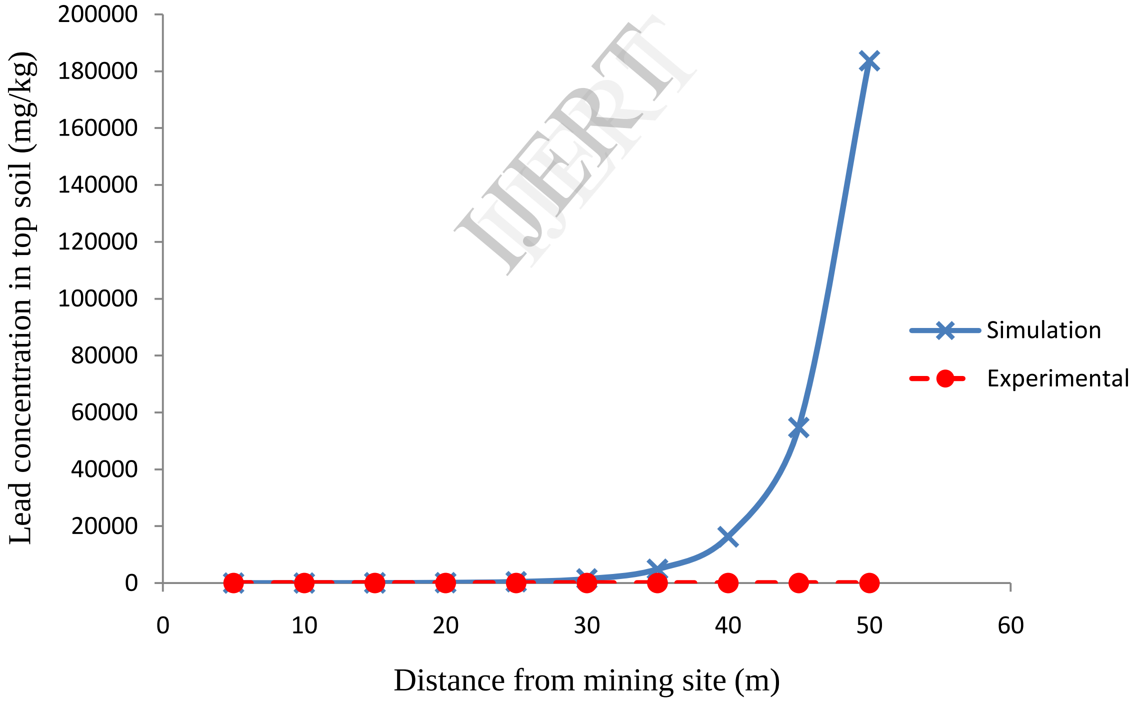

Figure 4.Lead concentrations in top-soil at various distances from mining site: East cardinal direction (from the results of Equation (3)).

The simulated results obtained for the four cardinal directions considered using Equation (3) showed a slight agreement with the experimental data for distances of 5 to about 30 m from the mining site, and a wide variation with the experimental data for longer distances from the mining site. However, the simulation results gave a characteristic curve showing continuous increase in lead concentration as the distance from the mining site increased. For example, the concentration of lead for top soil along the North cardinal direction was found to increase from 2.129 mg/kg to 1.44E+03 mg/kg from 5 m to about 30 m distance, and continued to increase till the concentration of 1.84E+05 mg/kg at a distance of 50 m. The correlation coefficients obtained between the simulation and experimental results which are negative values (-0.67788, -0.71531, -0.70267 and -0.6053 along

North, South, West and East cardinal directions respectively), also show that the results obtained from the predictive mathematical Equation (3) do not agree with experimental results. Therefore, Equation (3) has been discovered not to be suitable for the prediction of lead mobility in soil for this system.

Based on the above observation, Equation (5) was developed using different approaches and assumptions. The model was simulated and the results obtained were compared with the experimental data, accordingly. Figures 5 –16 showed the experimental results of lead concentration in soil samples obtained at an interval of 5 m from the mining location, as well as simulation results obtained for lead concentrations using the developed model Equation (5) for soil samples along the West, the North, the South and the East cardinal directions of the mining site.

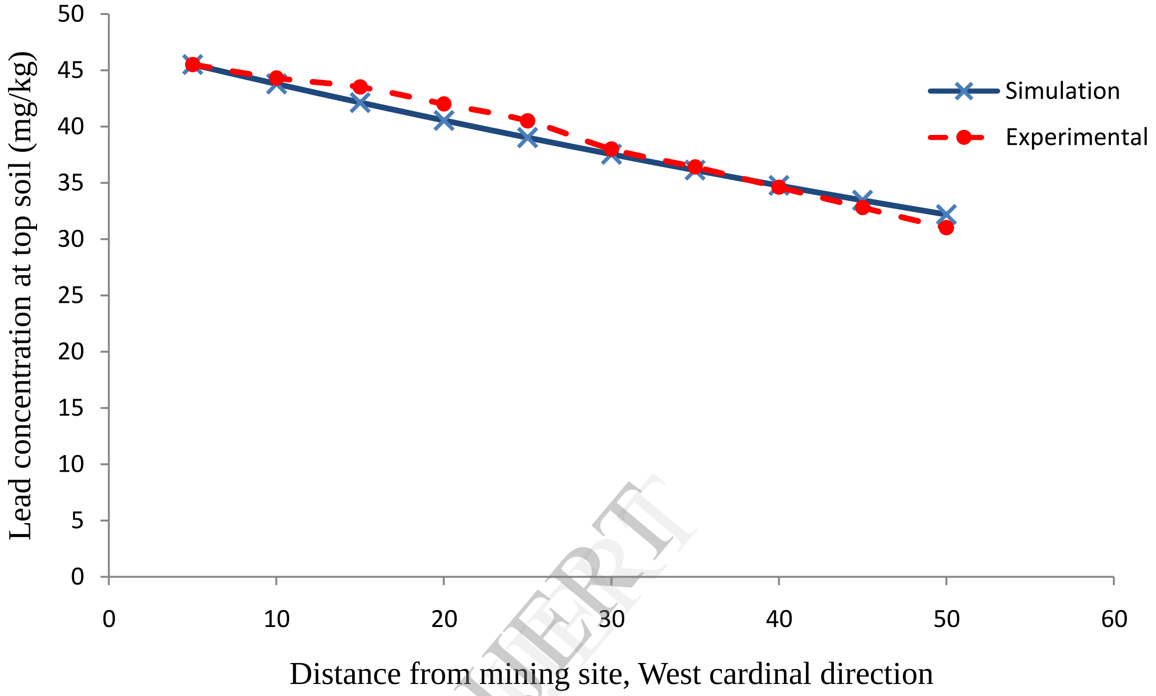

Figure 5. Lead concentrations in top-soil at various distances from mining site: West cardinal direction (from the results of Equation (5))

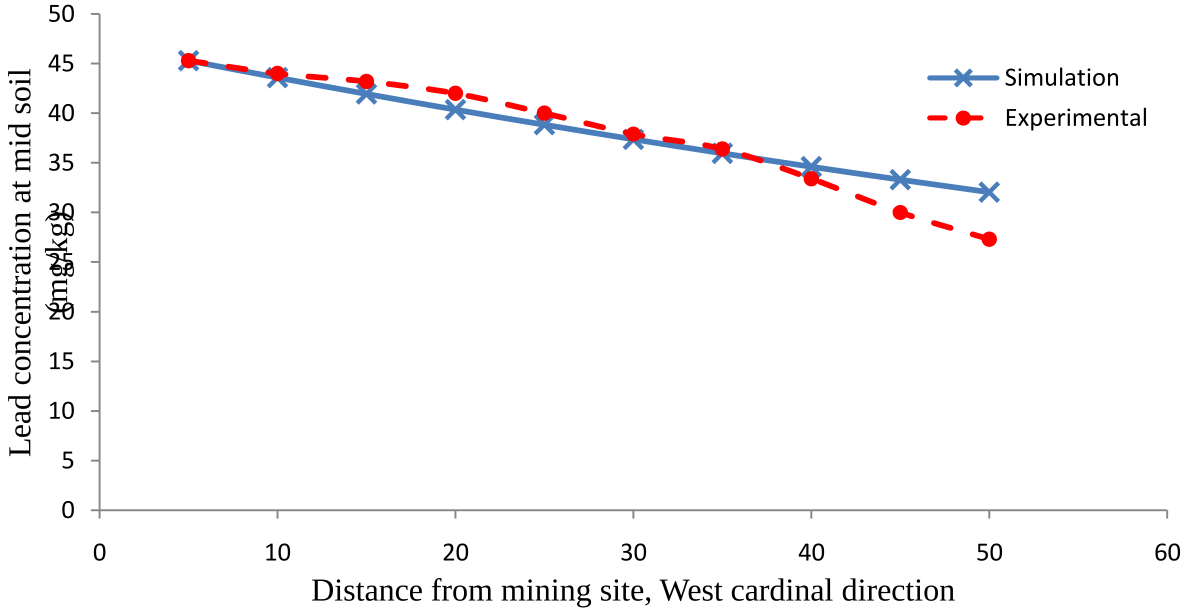

Figure 6. Lead concentrations in mid-soil at various distances from mining site: West cardinal direction (from the results of Equation (5))

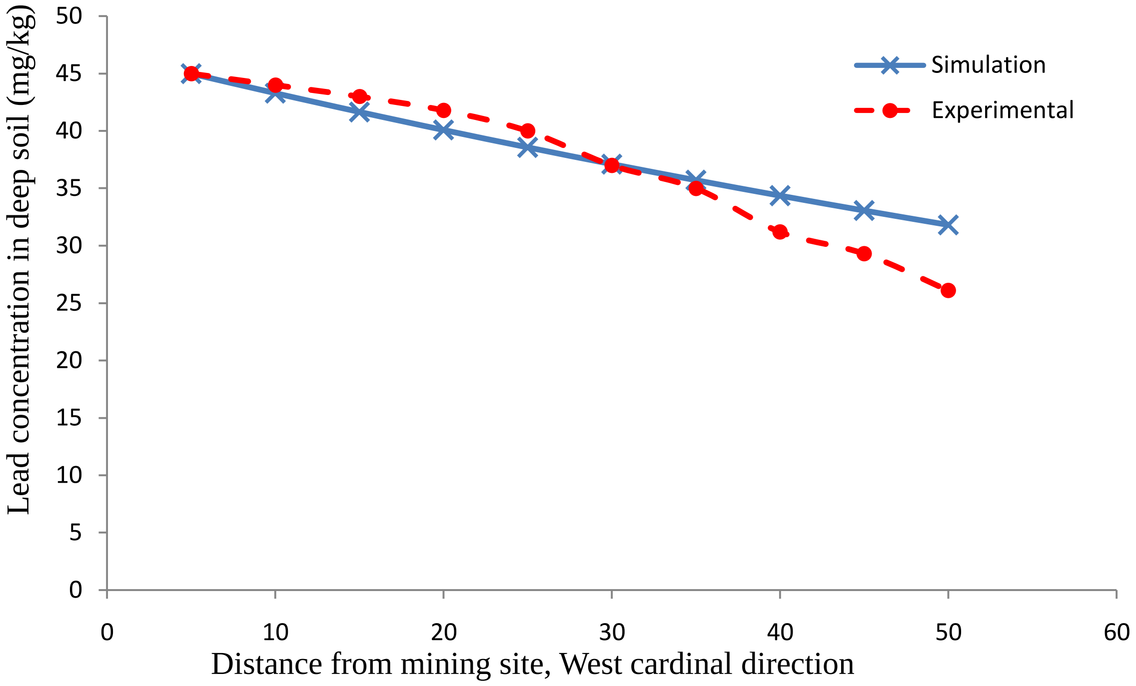

Figure 7. Lead concentrations in deep - soil at various distances from mining site: West cardinal direction (from the results of Equation (5))

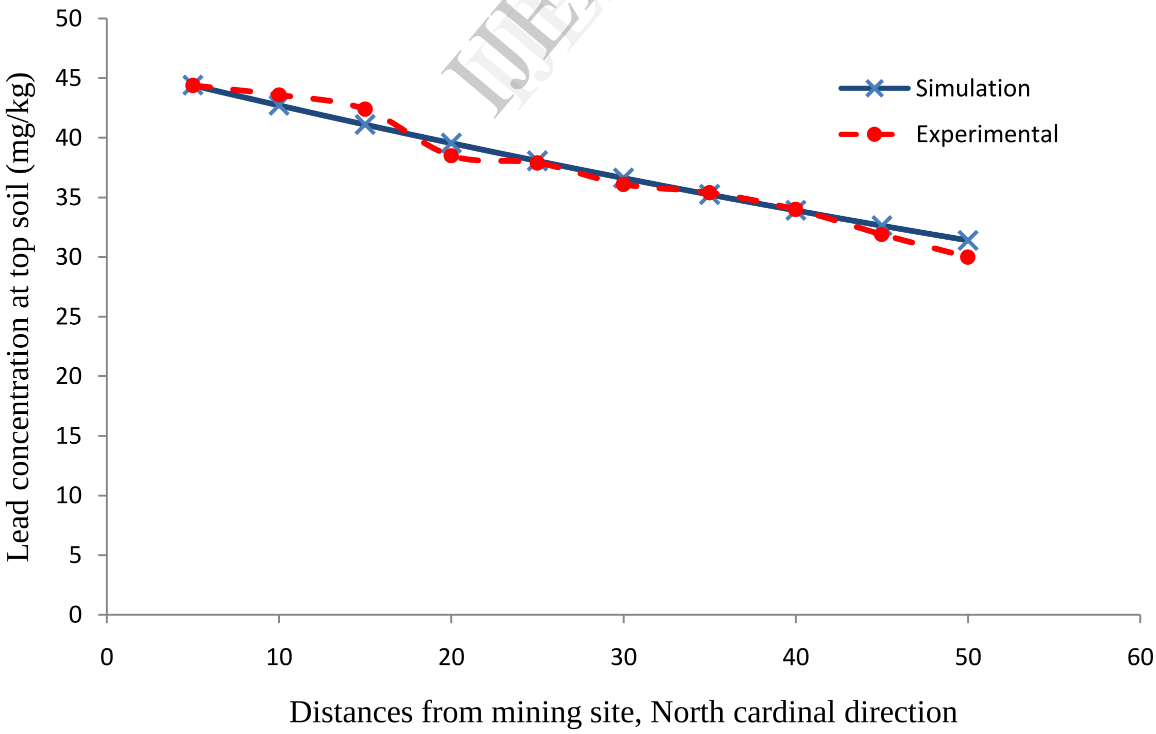

Figure 8. Lead concentrations in top-soil at various distances from mining site: North cardinal direction (from the results of Equation (5))

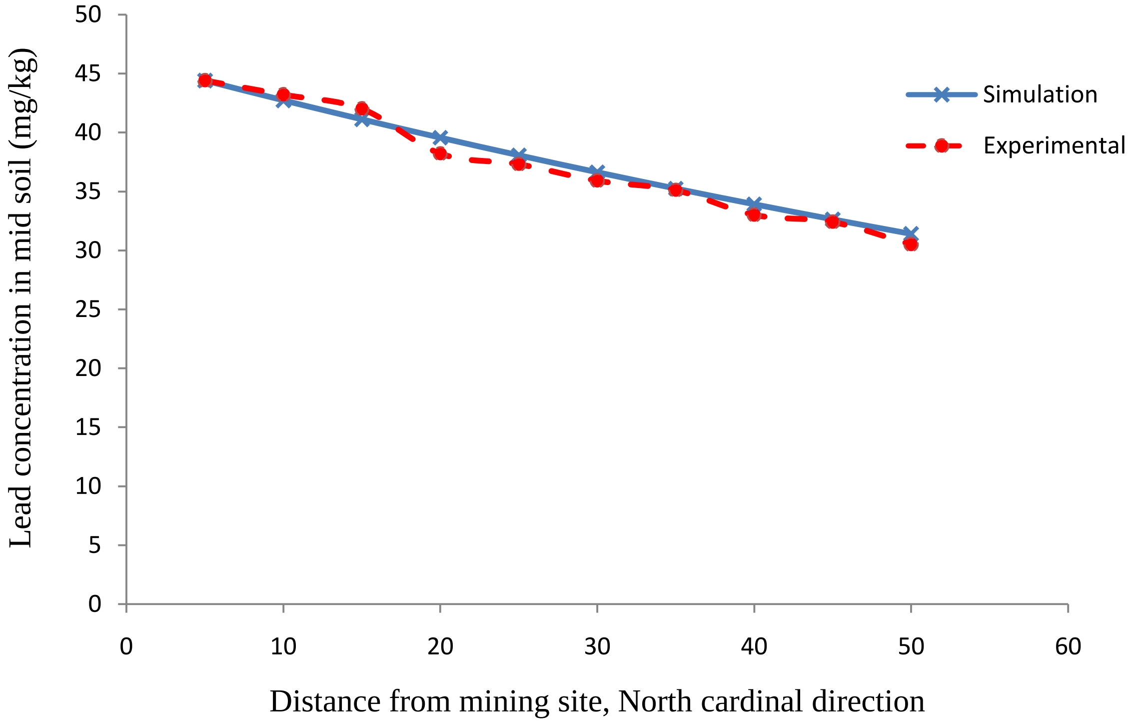

Figure 9. Lead concentrations in mid-soil at various distances from mining site: North cardinal direction (from the results of Equation (5))

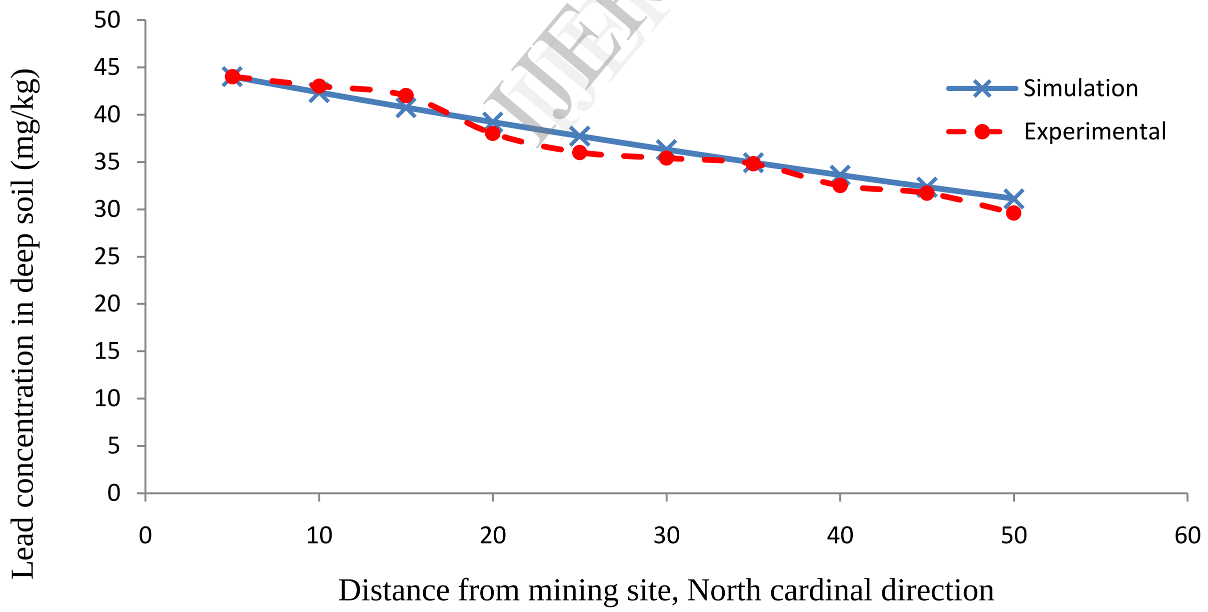

Figure 10. Lead concentrations in deep-soil at various distances from mining site: North cardinal direction (from the results of Equation (5))

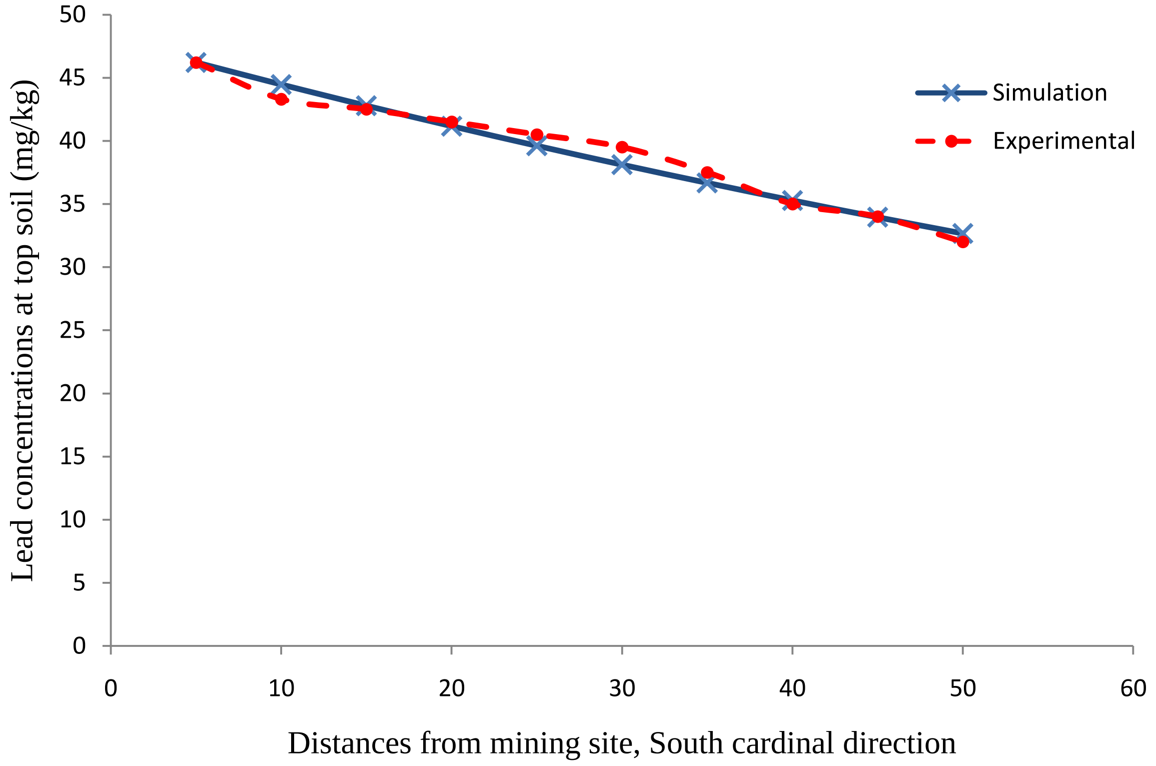

Figure 11. Lead concentrations in top-soil at various distances from mining site: South cardinal direction (from the results of Equation (5))

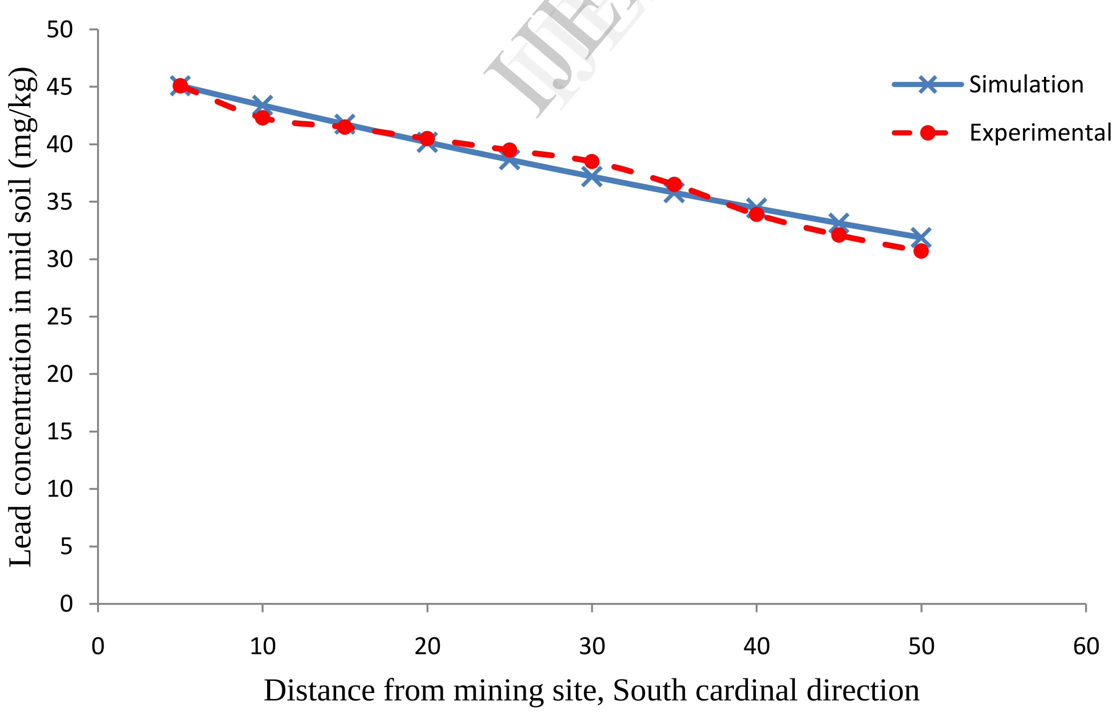

Figure 12. Lead concentrations in mid-soil at various distances from mining site: South cardinal direction (from the results of Equation (5))

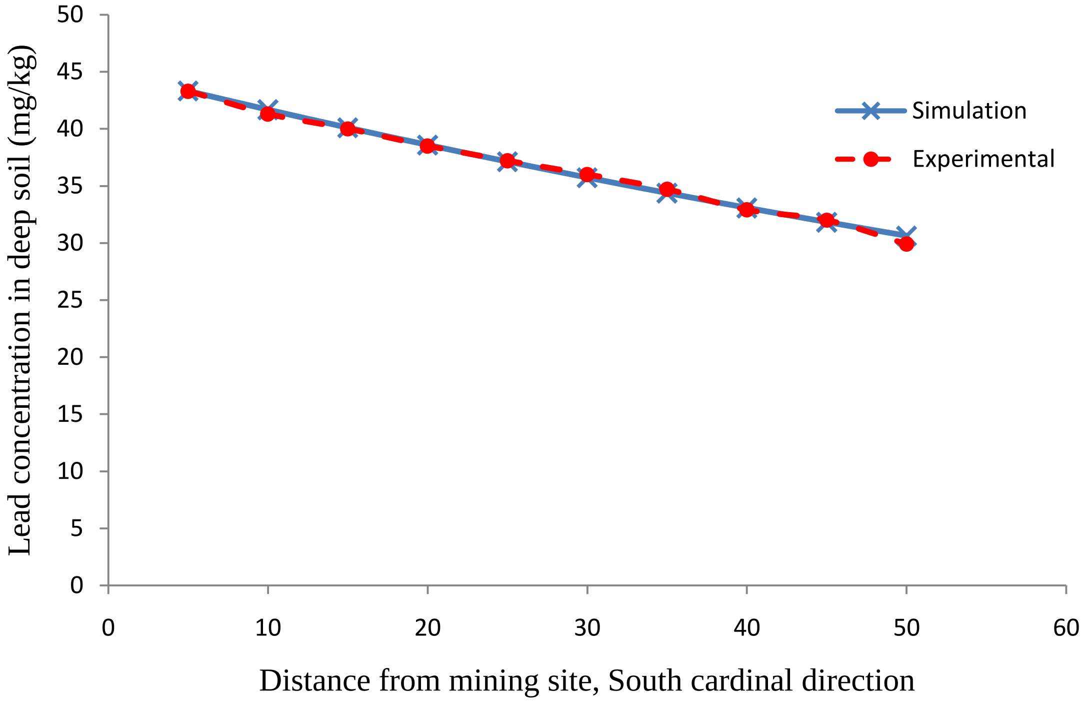

Figure13. Lead concentrations in deep-soil at various distances from mining site: South cardinal direction (from the results of Equation (5))

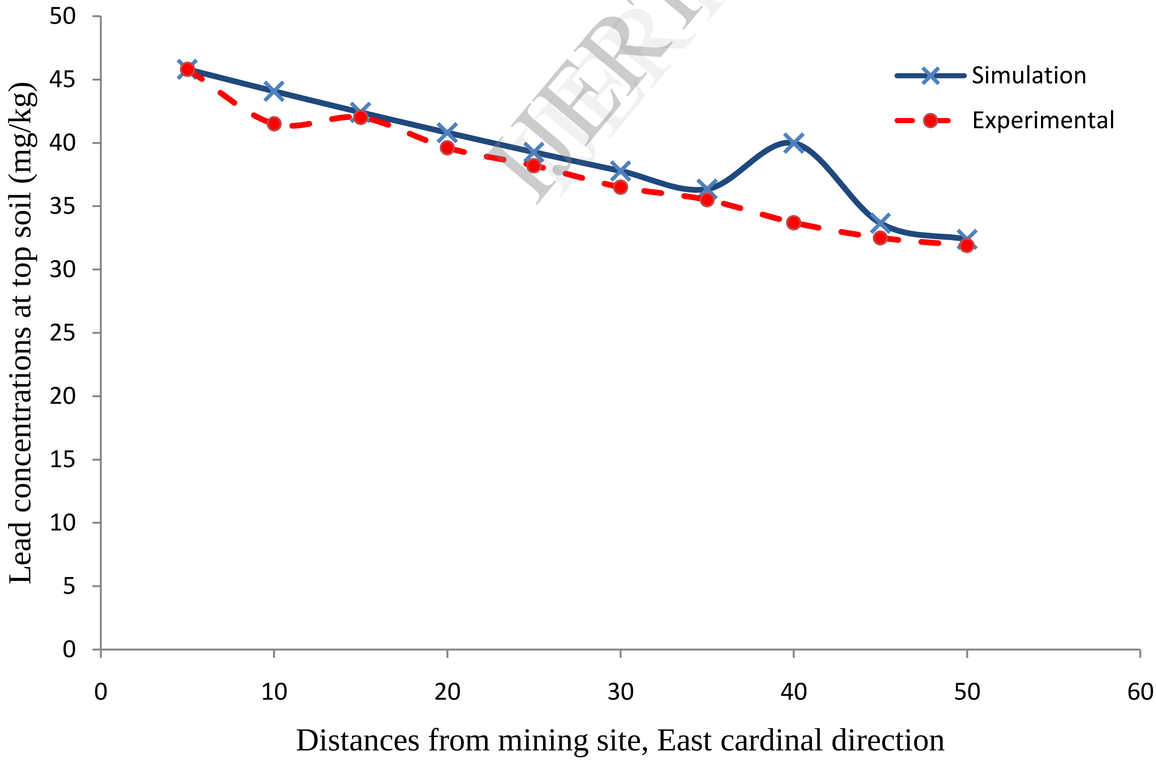

Figure 14. Lead concentrations in top-soil at various distances from mining site: East cardinal direction (from the results of Equation (5))

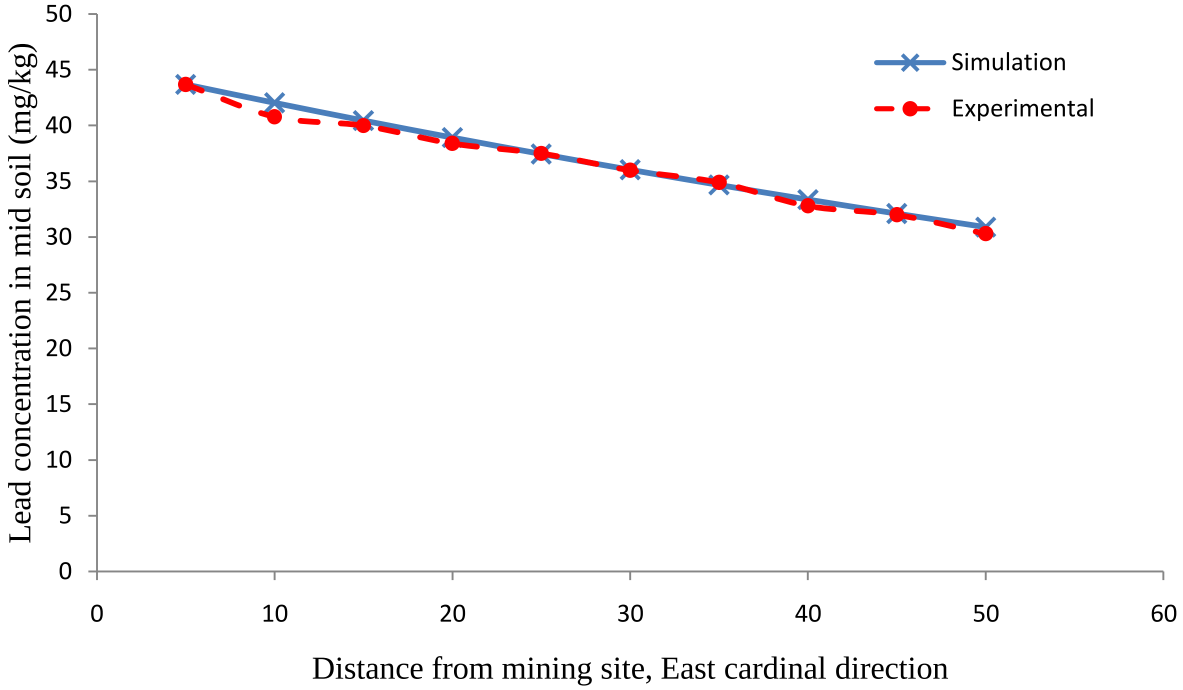

Figure 15. Lead concentrations in mid-soil at various distances from mining site: East cardinal direction (from the results of Equation (5))

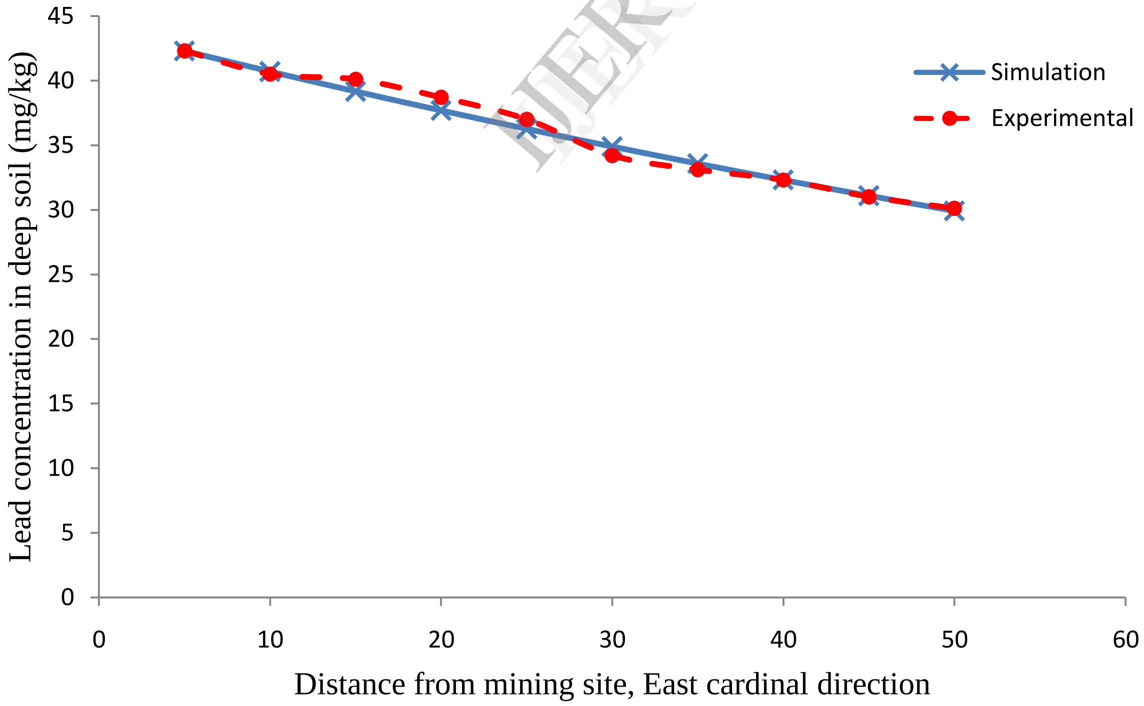

Figure 16. Lead concentrations in deep-soil at various distances from mining site: East cardinal direction (from the results of Equation (5))

Observing the experimental and the simulated results shown in Figures5-16 revealed the presence of lead in the soil samples obtained at various distances away from the mining site. Analysis of the results show that the lead concentration found in the soil samples obtained at various distances (5, 10, 15, 20, 25, 30, 35, 40, 45, 50 m) along the four different directions (West, North, East, and South) away from the mining site, decreased with increase in distance and depth, away from the mining site. For instance, the concentration of lead along the West cardinal direction in top soils decreased from 45.5 mg/kg at 5 m to 31.0 mg/kg at 50 m from the mining site, for mid-soil, it decreased from 45.30 mg/kg at 5 m to 27.30 mg/kg at 50 m, and for deep-soil, from 45 mg/kg at 5 m to 26.10 mg/kg at 50 m (Figures5-16). The simulation results obtained along the same West direction using the predictive mathematical model developed showed a very good agreement with the experimental data and with very similar graphical pattern. For example, for the top soil, the concentration of lead decreased from 45.5 mg/kg to 32.18 mg/kg, 45.3 mg/kg to 32.03 mg/kg in mid soil and 45.0 mg/kg to 31.82 mg/kg in deep-soil (Figure 5). Analysis of other simulated results for other investigated directions agreed quite well with the experiments in terms of data and graphical pattern (see Figures 6-16). The analyses also revealed that the results obtained in this study werebelow the maximum value of 420 mg/kg (420 ppm) specified by USEPA (Duruibe*et al.*, 2007), and below world average value of 15 mg/kg and also that of normal soil in the US. The concentration levels detected in the soil samples were higher than 0.13 mg/kg obtained from soils outside the lead mining site (control). This implies that the area under investigation was slightly polluted with lead and could get worst in the future since the mining activities are still ongoing at the site.

The observation maderegarding the concentration of lead in the soil samples made it to be concluded that the immediate farming lands around the mining site may be safe for crop plants cultivation due to the fact that the soils had total lead level less than 300 ppm. However, the high concentration values compared to the control gave room for serious concerns. Even though the mining activities taking place at Tunga Tsauni are not active compared to some other mining site, there is serious need to monitor and control the site properly because of the hazardous nature of lead pollution so that the possibilities of increasing the lead concentrations in the soils, water bodies and crop plants that will consequentially affect the inhabitants are adequately checked.

Based on the analyses presented and discussed so far, it is clear that the simulated results of lead concentration in soil samples have very good level of agreements with the experimental data measured. This is also supported with the values of the correlation coefficients obtained, which were 0.989689, 0.990525, 0.985546 and 0.988302 for the West, the North, the South and the East cardinal direction, respectively. Therefore, the mathematical model (Equation (5)) used can be considered as a good tool for predicting the lead concentrations in soil around the mining site at TungaTsauni, Gurara, Niger State, Nigeria.

4.0 CONCLUSIONS

From the results obtained in this work, it has been discovered that the concentration of lead in soil could be represented better using the model reported in the work ofTolessa (2004), Equation (5), than using the model developed from the convection-dispersion transport equation, Equation (3). It was also discovered from the simulations carried out using Equation (5) that the concentration of lead in soil decreased with increase in distance and depth. Furthermore, the results of the simulations using Equation (5) were found to be in good agreements with the experimental values with the correlation coefficient valuesof 0.989689, 0.990525, 0.985546 and 0.988302 along the West, the North, the South and the East cardinal directions from the lead mining site, respectively, whereas, the correlation coefficients obtained from the simulations of the other model (Equation (3)) were found to be negative. Therefore, Equation (5) has been discovered to be a true representation of the phenomenon of lead metal mobility in the soil of. It is hoped that the model (Equation (5)) will be a good expression for the prediction of lead mobility in soil so as to ascertain the safe areas for agricultural activities in Tunga Tsauni town.

Considering the associated defect reported in past studies on the physical transport models of chemical pollutants in soil matrix, it is recommended that artificial neural networks be applied to the modeling of the mobility of lead in soil so as to be able to capture the complexities occurring in the phenomenon.

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