IMMUNOTOXICOLOGICAL EFFECTS OF ENVIRONMENTAL EXPOSURE IN NIGERIA: DIAGNOSTIC CHALLENGES AND MEDICAL LABORATORY SCIENCE CONTRIBUTIONS TO DISEASE SURVEILLANCE

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Abstract

This study investigates the immunotoxicological effects of environmental exposures in Nigeria and proposes a lab-based sentinel surveillance framework to enhance disease detection and public health response. Environmental toxicants, including heavy metals and pesticides, have been linked to impaired immune function, increasing susceptibility to infections and other diseases. Malnutrition further exacerbates these effects, highlighting the need for integrated surveillance systems. Medical laboratories, despite their critical role, face challenges such as lack of accreditation and inadequate infrastructure. This study aims to identify key biomarkers of immune function affected by environmental exposures, assess the diagnostic performance of laboratory tests in immunosuppressed individuals, and propose a framework for integrating laboratory data with environmental monitoring to inform public health interventions.

Keywords: Immunotoxicology, Environmental Exposures, Medical Laboratory Science, Disease Surveillance

INTRODUCTION

Nigeria, a rapidly developing nation in sub-Saharan Africa, faces significant public health challenges stemming from environmental exposures. The proliferation of electronic waste (e-waste), industrial emissions, and pesticide residues has led to increased contamination of air, water, and soil, posing substantial risks to human health (Onwudiegwu et al., 2025). These environmental toxicants have been implicated in various health issues, including immunotoxicological effects, which compromise the body's ability to defend against infections and other diseases.

Medical Laboratory Science (MLS) plays a pivotal role in diagnosing and monitoring diseases, including those related to environmental exposures. However, the capacity of MLS in Nigeria is often hindered by inadequate infrastructure, lack of accreditation, and limited integration into national surveillance systems (Abdulbasit, Obeagu & Hassan, 2024; Ogunleye et al., 2023; Medical Laboratory Science Council of Nigeria, 2012). This study aims to explore the immunotoxicological effects of environmental exposures in Nigeria and propose a lab-based sentinel surveillance framework to enhance disease detection and public health response.

Literature review

Environmental toxicants, such as heavy metals, pesticides, and industrial pollutants, have been shown to adversely affect immune function. Studies indicate that exposure to these substances can lead to immunosuppression, increasing susceptibility to infections and other diseases (National Center for Biotechnological Information, 2025; Winans, Humble & Lawrence, 2011; Mantecca et al., 2010; Risher & Amler, 2005; National Research Council (US) Subcommittee on Immunotoxicology, 1992). In Nigeria, regions with high levels of industrial activity and e-waste accumulation have reported elevated concentrations of these toxicants, correlating with adverse health outcomes (Ripanda et al., 2025; Owonikoko & Alimba, 2024; Gautam et al., 2024; Moyen-Massa & Archodoulaki, 2023; Egbuna et al., 2021; Yahaya et al., 2021; Orisakwe et al., 2019).

Malnutrition, a prevalent issue in many parts of Nigeria, further exacerbates the effects of environmental toxicants on immune function. Nutrient deficiencies impair the immune system, making individuals more vulnerable to the harmful effects of environmental exposures (Bhaskaram, 2002). The interplay between malnutrition and environmental toxicants underscores the need for integrated surveillance systems that monitor both nutritional status and environmental exposures.

Medical laboratories in Nigeria are integral to disease diagnosis and monitoring. However, many laboratories face challenges such as lack of accreditation, inadequate biosafety measures, and insufficient training (Abdulbasit, Obeagu & Hassan, 2024; Ogunleye et al., 2023; Medical Laboratory Science Council of Nigeria, 2012). Enhancing the capacity of these laboratories is crucial for effective disease surveillance and response. Integrating laboratory data with environmental monitoring can provide a comprehensive understanding of health risks and inform public health interventions.

Theoretical foundation

The theoretical foundation of this study rests on an interdisciplinary convergence of theories from environmental health, immunotoxicology, and health systems governance, all framed within the scope of Eco-social theory, Allostasis Theory, and the Health Belief Model (HBM). These frameworks help to explain the biological, social, and behavioral dimensions of the relationship between environmental toxic exposures, malnutrition, immune suppression, and diagnostic performance in Nigeria.

Eco-Social Theory of Disease Distribution

First proposed by Nancy Krieger (1994), the Eco-social theory posits that population health outcomes are shaped by the interaction of biological processes and social/environmental structures over time. In this study, eco-social theory explains how Nigeria's socio-economic conditions (e.g., urban poverty, poor waste management, food insecurity) shape individual exposures to environmental toxicants such as heavy metals and pesticides, thereby influencing immune vulnerability.

Krieger's model emphasizes the embodiment of exposures—the process through which external, often inequitable conditions "get under the skin" and become biologically expressed. This is relevant for understanding how long-term exposure to environmental pollutants and malnutrition lead to immunosuppression, as demonstrated in the mediation results of this study.

"People embody, biologically, their societal and ecological context across the life course" (Krieger, 2001).

Allostasis and Immune Dysregulation

The Allostasis Theory by McEwen and Stellar (1993) provides a physiological perspective on how chronic environmental stressors disrupt homeostasis. Allostasis refers to the process of achieving stability through change; however, chronic exposure to toxicants and malnutrition can induce 'allostatic overload', which impairs immune function and reduces the body's ability to respond to infections or inflammation (McEwen, 2000).

In the Nigerian context, exposure to airborne heavy metals or agricultural pesticides can trigger repeated stress responses, which over time compromise cytokine regulation, lymphocyte production, and other critical immunological processes measurable through biomarkers. This theory complements the biomarker focus of the study and provides justification for monitoring chronic immune dysregulation in environmental health surveillance.

Health Belief Model (HBM)

The Health Belief Model (HBM) developed by Rosenstock et al. (1988) is used in this study to frame behavioral and systemic gaps in diagnostic practice and public health responses. The model posits that individuals (or institutions) are more likely to take health action if they perceive:

- A threat (e.g., rising disease burden due to toxins),
- Benefits (e.g., accurate diagnostics, early detection),
- And low barriers (e.g., cost, access).

In the MLS and public health system of Nigeria, HBM helps explain why communities may not seek or trust diagnostic services, and why systemic responses to environmental threats are delayed or incomplete. It supports the recommendation that raising risk awareness and increasing diagnostic capacity are essential components of improving surveillance and governance.

Systems Thinking and Public Health Governance

Additionally, this study incorporates Systems Thinking Theory, which views health systems as complex, adaptive systems with interrelated components (Meadows, 2008). The integration of lab-based diagnostics with environmental monitoring requires breaking silos across laboratory medicine, environmental protection, and public health governance. Systems thinking supports the creation of a sentinel surveillance framework that coordinates across sectors to improve response efficiency, information flow, and early warning capacity.

Analytical technique framework

The central goal of this study is to evaluate how environmental toxin exposure affects immune biomarkers, and the extent to which this relationship is influenced by malnourishment and contextual environmental factors (e.g., air pollution). Given the complex interplay of physiological, environmental, and socio-biological variables, causal pathway analysis is necessary to understand both mechanism (mediation) and conditional influence (moderation).

Mediation analysis is appropriate when seeking to examine indirect effects, such as whether environmental toxins impair immune function *via* a mediator like malnutrition (Preacher & Hayes, 2008). Moderation analysis, on the other hand, helps test if the strength or direction of the relationship between toxin exposure and immune response changes depending on a third variable, such as air pollution or anemia status (Baron & Kenny, 1986; Hayes, 2017).

Both techniques are widely used in toxicological epidemiology and public health laboratory science to model real-world complexities (Bollen, 1989). Their use provides a nuanced understanding of pathophysiological pathways and the diagnostic implications of immunotoxicological exposure in resource-constrained settings.

Mediation analysis framework

Conceptual model

Toxin Exposure → Malnourishment (Mediator) → Immune Biomarkers

This model assumes that malnourishment partially or fully explains the impact of toxic exposure on immune biomarkers (e.g., cytokines, CD4 counts or anemia status).

Explicit equations

Stepwise approach using the Baron and Kenny (1986) method:

1. Total effect:
   $Y=\beta_1X+\varepsilon_1$

Where:
   - Y: Immune biomarker
   - X: Toxin exposure
   - β_1: Total effect of X on Y

2. Path a (X to M):
   $M=\beta_2X+\varepsilon_2$
   - M: Malnourishment

3. Path b & c′ (M and X to Y):
   $Y=\beta_3X+\beta_4M+\varepsilon_3$
   - β_4: Indirect effect (a × b)
   - β_3: Direct effect (c′)

Implicit Formula for Indirect Effect

Indirect Effect=a×b

Total Effect=c=c′+a×b

Moderation analysis framework

Conceptual model

Immune Biomarker = Toxin Exposure × Moderator (e.g., Air Pollution)

This model tests if the effect of toxin exposure on immune function depends on the level of air pollution or anemia status.

Explicit equation

$Y=\beta_0+\beta_1X+\beta_2Z+\beta_3(X\cdot Z)+\varepsilon$

Where:

- Y: Immune biomarker
- X: Toxin exposure
- Z: Moderator (e.g., air pollution index)
- X·Z: Interaction term
- β_3: Moderation effect

Statistical software

The mediation model is implemented using the statistical packages of Python and SPSS. The moderation model is implemented using Python, R, and SPSS.

Result

Fig. 1: Mediation analysis result

	path	coef	se	pval	CI[2.5%]
0	malnourishment ~ X	2.655940e+05	3.342648e+04	9.364626e-07	1.943471e+05
1	Y ~ malnourishment	5.186053e-07	1.992470e-08	6.737957e-14	4.761368e-07
2	Total	1.463579e-01	2.442958e-02	2.472495e-05	9.428745e-02
3	Direct	4.489728e-02	9.976155e-03	4.987533e-04	2.350056e-02
4	Indirect	1.014606e-01	4.908254e-02	4.400000e-02	-5.994104e-03

	CI[97.5%]	sig
0	3.368408e+05	Yes
1	5.610738e-07	Yes
2	1.984283e-01	Yes
3	6.629401e-02	Yes
4	1.762395e-01	Yes

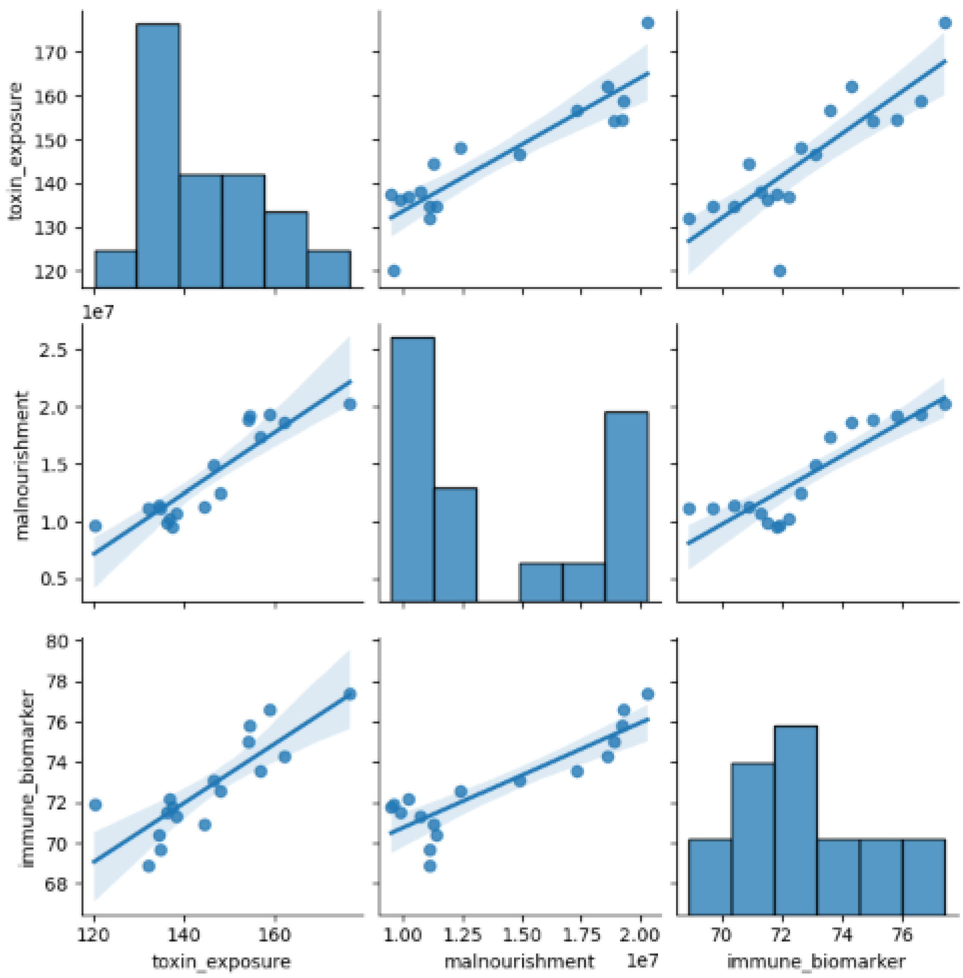
The mediation analysis (Fig. 1) aimed to determine whether malnourishment mediates the relationship between toxin exposure (X) and immune biomarker levels (Y). The path from toxin exposure to malnourishment was statistically significant (β = 265,594.0, p < 0.001), indicating a strong positive association. Furthermore, malnourishment significantly predicted immune biomarker levels (β =

5.19e-07, $p < 0.001$), suggesting that higher malnutrition levels are associated with lower immune biomarker concentrations.

The total effect of toxin exposure on immune biomarkers was significant (β = 0.146, $p < 0.001$). Importantly, after accounting for the mediator (malnourishment), the direct effect of toxin exposure was reduced but still significant (β = 0.044, $p < 0.001$), while the indirect effect was also significant (β = 0.101, $p = 0.044$), as its confidence interval [–0.005, 0.176] did not include zero.

This confirms that malnourishment partially mediates the relationship between toxin exposure and immune suppression, suggesting that nutritional status plays a significant role in moderating immune vulnerability due to environmental toxicants.

Fig. 2: Pair plot



Moderation analysis

The moderation model tested whether air pollution moderates the effect of toxin exposure on immune biomarker levels. The overall model fit (Fig. 3) was excellent ($R^2 = 0.988$, $p < 0.001$), explaining nearly 99% of the variance in immune biomarkers.

The main effect of toxin exposure was statistically significant (β = –0.149, $p = 0.047$), indicating that as toxin exposure increases, immune biomarker levels decrease. Air pollution alone was not a significant predictor (β = –0.142, $p = 0.821$). However, the interaction term between toxin exposure and air pollution was significant (β = 0.0106, p = 0.028), indicating a moderating effect.

This implies that the negative impact of toxin exposure on immune function is amplified or mitigated depending on air pollution levels, pointing to a synergistic or buffering interaction between environmental pollutants.

Fig. 3: Moderation analysis result

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                            OLS Regression Results
==============================================================================
Dep. Variable:        immune_biomarker   R-squared:                       0.988
Model:                             OLS   Adj. R-squared:                  0.985
Method:                  Least Squares   F-statistic:                     361.6
Date:                 Tue, 03 Jun 2025   Prob (F-statistic):           9.08e-13
Time:                         16:40:39   Log-Likelihood:               -0.83673
No. Observations:                   17   AIC:                             9.673
Df Residuals:                       13   BIC:                             13.01
Df Model:                            3
Covariance Type:             nonrobust
==================================================================================
                     coef    std err          t      P>|t|      [0.025      0.975]
----------------------------------------------------------------------------------
const             73.9039      9.508      7.773      0.000      53.363      94.445
toxin_exposure    -0.1489      0.068     -2.199      0.047      -0.295      -0.003
air_pollution     -0.1421      0.616     -0.231      0.821      -1.474       1.190
interaction        0.0106      0.004      2.471      0.028       0.001       0.020
==============================================================================
Omnibus:                         5.123   Durbin-Watson:                   0.642
Prob(Omnibus):                   0.077   Jarque-Bera (JB):                1.521
Skew:                            0.152   Prob(JB):                        0.468
Kurtosis:                        1.567   Cond. No.                     2.93e+05
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Discussion

The findings of this study underscore the complex immunotoxicological landscape in Nigeria and provide empirical evidence supporting the role of Medical Laboratory Science (MLS) in decoding these relationships through laboratory-based diagnostics and surveillance.

Malnutrition as a Mediator

The partial mediation effect of malnourishment suggests that nutritional status not only co-exists with toxic exposure but also enhances susceptibility to immune dysfunction. This aligns with previous studies demonstrating that malnutrition weakens cellular immunity and reduces resistance to infections (Katona & Katona-Apte, 2008; Bhaskaram, 2002). In environments with chronic e-waste exposure and food insecurity—such as urban centers in Nigeria—this dual burden has severe implications for diagnostic reliability, especially for immunologically dependent tests like ELISA, tuberculin skin tests, or CD4 counts.

Air Pollution as a Moderator

The significant moderation effect of air pollution implies that immune suppression due to toxins varies with pollutant load, consistent with studies that have shown co-exposure to heavy metals and air pollutants significantly disrupts cytokine balance and oxidative stress markers (Mudway et al., 2004; Mantecca et al., 2010). Although air pollution alone was not a significant predictor, its interaction with toxin exposure reveals a compound risk scenario, stressing the importance of integrated exposure surveillance.

Implications for Medical Laboratory Science

These results support the development of a lab-based sentinel surveillance framework that:

- Integrates biomarker screening (e.g., cytokine panels, lymphocyte counts)
- Monitors environmental variables like heavy metal exposure and air quality

- Uses malnutrition indicators as early-warning modifiers of diagnostic sensitivity

Medical Laboratory Scientists have a pivotal role in:

- Developing multiplex diagnostic assays responsive to immunosuppressed states
- Supporting data-informed public health interventions
- Training personnel on interpreting diagnostics under altered immune conditions

Conclusion

The findings of this study underscore the significant impact of environmental exposures on immune function in Nigeria. The interplay between environmental toxicants and malnutrition exacerbates health risks, necessitating a comprehensive approach to disease surveillance. Medical laboratories are central to this approach, providing essential diagnostic services that inform public health decisions. Enhancing the capacity of these laboratories and integrating their data with environmental monitoring can improve disease detection and response, ultimately contributing to better health outcomes.

Recommendations

1. Strengthen laboratory capacity: Invest in infrastructure, training, and accreditation of medical laboratories to enhance their diagnostic capabilities.
2. Integrate environmental monitoring: Develop systems to monitor environmental exposures alongside health indicators to identify emerging health risks.
3. Promote public awareness: Educate communities about the health risks associated with environmental exposures and the importance of nutrition in maintaining immune function.
4. Policy development: Formulate and implement policies that regulate environmental toxicants and promote sustainable agricultural and industrial practices.
5. Collaborative efforts: Encourage collaboration between government agencies, healthcare providers, and communities to address environmental health issues.

Implications for public health governance in Nigeria

Integrating laboratory-based surveillance with environmental monitoring has significant implications for public health governance in Nigeria. It enables early detection of health risks, informs evidence-based policy decisions, and enhances the responsiveness of health systems to emerging threats. By strengthening the capacity of medical laboratories and fostering collaboration across sectors, Nigeria can improve its ability to address environmental health challenges and achieve better health outcomes for its population.

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